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SUPERGENE SPHALERITE, GALENA AND WILLEMITE AT BALMAT, N. Y.[1]

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THE following pages include a description of the occurrence of willemite, chlorite, hematite, ilvaite and magnetite, and of a second generation of sphalerite, galena and chalcopyrite, believed to be of supergene origin.

PREVIOUS VIEWS REGARDING SUPERGENE SPHALERITE AND GALENA.

The literature of supergene sulphide enrichment deals mainly with ores of copper and silver; many attempts to find parallels in the other common ores, such as those of lead and zinc, have been virtually fruitless. Current opinion is summarized by Lindgren[2] in the statement that "well-defined zones of supergene sulphides are common only in the case of copper and silver. . . . No great

[1] Presented before Society of Economic Geologists and Amer. Inst. Min. Eng., New York, Feb., 1935. See also Brown, John S.: Structure and Primary Mineralization of the Zinc Mine at Balmat, N. Y. ECON. GEOL., vol. 31, pp. 233–258, 1936.

[2] Lindgren, W.: Mineral Deposits, 4th ed., p. 825, 1933.

zones of supergene lead or zinc sulphides are known." Further, regarding sphalerite, he states (p. 853) that "no case has been recorded where it replaces pyrite, as chalcocite so often does." So also Emmons,[3] one of the chief contributors to the literature of downward enrichment, states that although the formation of supergene lead and zinc sulphides from mine waters in old workings is a matter of record, and likewise, although "there are many examples of zinc sulphide reprecipitated below the water level, yet no great supergene zones of zinc sulphide are known, and supergene sphalerite replacing other sulphides is rare, if it exists at all."

Notwithstanding the lack of definite examples of the supergene enrichment of lead and zinc sulphides, many writers have pointed out that, according to the principle commonly referred to as Schürmann's law, lead sulphide, taken into solution under oxidizing conditions, should be capable of replacing sphalerite or pyrite, and sphalerite in like manner should replace pyrite. It has been suggested that the failure to find examples of this process in nature is due to the lack of features to distinguish it. Thus Ries[4] concludes that "it is difficult to distinguish secondary lead and zinc minerals from primary ones, because they are the same in each case, and while they no doubt occur, few well defined cases have been described."

In view of the long negative history of the search for supergene lead and zinc sulphides, it was with much interest that the writer noted, early in the development of the Balmat mine, evidence of a well defined zone of secondary sphalerite and galena on a commercial scale. It was remarkable to find this condition in a region of little relief at an altitude of only 700 feet above sea-level, yet definitely recognizable to 1000 feet in depth, or well below the present sea-level.

Recognition of this situation is not original. The existence of oxidation accompanied by secondary sphalerite near Balmat was

[3] Emmons, W. H.: Ore Deposits of the Western United States, p. 417, chapter on supergene enrichment, Amer. Inst. Min. Eng., 1933.

[4] Ries, H.: Economic Geology, 5th ed., p. 486, 1925.

succinctly stated by Newland [5] in 1917 and again by Smyth [6] in 1918. The specific instance was a small prospect (the Dominion Company) included in the Balmat property, but somewhat removed from the commercial ore bodies. Here a gossan of hematite was explored for iron ore many years ago and found unsuitable. Pyrite appeared at a depth of about 25 feet, and the hematite was of low grade and siliceous. Later exploration to a depth of 135 feet on the incline, showed the complete change of the small lens of mineral into a mixture of pyrite and zinc sulphide with some iron oxide and quartz. In this mixture Newland and Smyth noted the presence of a later generation of sphalerite which they interpreted as related to the evident oxidation, and therefore supergene.

EVIDENCES OF DEEP SOLUTION AND OXIDATION.

Solution Cavities.—Evidence that surface waters have penetrated to surprising depths and accomplished important changes in the Edwards district is afforded by cavities obviously due to solution of limestone by ground water. These are encountered in mine workings and in drill holes, and are indicated in many cases by surface sinks and underground drainage, although glaciation has obliterated much of this surface evidence. The evidence of underground solution at Balmat is intimately related to the origin of Sylvia Lake, which is immediately west of the Balmat mine. In relation to its area of 330 acres, this lake is of unusual depth, averaging 50 to 75 feet in its southern lobe, and 100 to 150 feet in the northern part. In this and other respects it differs considerably from the average lake of similar size produced by glacial damming or scour. Prospecting by diamond drill from the ice was attempted in the southern end of the lake in 1929, but was found difficult. Beneath the water a deposit of

[5] Newland, D. H.: Zinc-Pyrite Deposits of the Edwards District, St. Lawrence Co., N. Y. New York State Defense Council, Bull. 2, 1917.

Cushing, H. P. and Newland, D. H.: Geology of the Gouverneur Quadrangle, N. Y. New York State Mus. Bull. 259, pp. 100–101, 1925.

[6] Smyth, C. H. Jr.: Genesis of the Zinc Ores of the Edwards District, St. Lawrence Co., N. Y. New York State Mus. Bull. 201, pp. 27–28, 1918.

alluvial silt and sand from 50 to 150 feet in thickness was encountered, and below that the rock was broken and cavernous to unknown depths. A typical core disclosed foreign boulders of gneiss and granite in limestone cavities at a depth of 280 feet, and was abandoned in a cavity filled with quicksand at 365 feet. The conclusion seems warranted that Sylvia Lake is a deep preglacial sink-hole, partly filled with drift.

As additional evidence of underground drainage, two or three small streams northeast of Balmat disappear into limestone. Small cavities yielding a moderate flow of water have also been encountered at various places underground in the walls of the ore bodies.

The Edwards mine has yielded a considerable flow of water (about 500 gallons per minute), continuously from the surface downward. This issues from visible cavities and solution channels generally in or near some of the ore bodies. The cavities seldom exceed a few feet in size, but are present at all levels down to 1200 feet. All known ore-bodies have been developed on the 1500-foot level, however, without encountering cavities or water, so that apparently this condition does not extend much below the 1200-foot level. The Edwards mine also has an associated sink-hole structure which was concealed by drift but was inadvertently tapped in mining on the 240-foot level in 1924. A deluge of silt and mud virtually filled the mine to the 900-foot level and a hole 300 feet across and more than 100 feet deep was left at the surface.

It might be suggested that these cavities were formed by deep-seated solutions associated with ore deposition, but their distribution does not accord with this theory. No cavities of any size are found actually within the ore, but commonly in the walls of ore bodies and the largest ones at a considerable distance away. Moreover, they are widespread throughout the limestone far from any association with zinc deposits. In some cases the cavities contain mud and boulders clearly derived from surface residues.

Oxidation Products.—Minerals that can be demonstrated to

have formed by oxidation constitute the most important evidence from the viewpoint of supergene enrichment processes. Of these, the most abundant and significant is earthy red hematite, which occurs in the vicinity of bodies of pyrite in a manner clearly indicating its derivation by oxidation of the pyrite. Since the earthy red hematite is accompanied by smaller amounts of hard blue hematite in relations which show their contemporaneity, these evidently have the same significance. And, since still smaller amounts of crystalline specularite are associated with these two in a manner unmistakably indicating a similar origin, this also must be a product of the same agencies. Magnetite, likewise, occurs at Balmat in a manner which indicates its derivation from pyrite, evidently by oxidation.

Chlorite is another abundant mineral which, at Balmat and elsewhere in the region, appears to be chiefly of supergene origin. Since much chlorite in other districts undoubtedly results from deep-seated hydrothermal alteration, this conclusion may be questioned and evidence in its support will be given later. The same condition will apply to ilvaite, a minor associate of chlorite at Balmat. Finally, willemite is a mineral which at Balmat seems clearly to be the result of oxidation.

Hematite Mines.—The best evidence of extensive oxidation and solution by underground waters in the region would be that afforded by the hematite mines, if it were more accurately available. The last of these ceased operation in 1907 and no adequate geological account of them ever appeared in print. Some general facts and inferences are available,[7] however, and the writer has examined the dumps and surface showings and made limited petrographic studies of the ore and wall rocks.

The principal hematite mines were near Keene and Antwerp, 8 miles west of Balmat. The prevailing formation is Grenville limestone, overlain by remnants of Upper Cambrian Potsdam sandstone. The Potsdam was deposited on a pre-Cambrian sur-

[7] Newland, D. H.: Mineral Resources of the State of New York. New York State Mus. Bull. 223–224, pp. 126–129, 1921. Buddington, A. F.: Report on the Pyrite and Pyrrhotite Veins in Jefferson and St. Lawrence Counties, N. Y. New York State Defense Council, Bull. 1, 1917.

face of moderate relief, ranging from 200 to 400 feet. The pre-Cambrian drainage was adjusted to structure and the deeper valleys, carved on limestone, are now filled with remnants of Potsdam.

Interbedded in the limestone is a band of pyritic gneiss 100 to 200 feet thick, commonly rusty and weathered at the outcrop, which constituted a ridge in the pre-Cambrian topography. The pyrite content at many places is great enough to have attracted attention as a possible source of commercial pyrite, and a similar, if not identical, band was mined northeast of Gouverneur. The hematite mines are associated with the pyrite band in a manner which scarcely admits of doubt that the hematite has been derived by oxidation of the pyrite. The hematite ores are commonly in the hanging-wall of the pyritic band, less commonly in the foot-wall. Commercial ore was found chiefly in the overlying limestone and the upper portion of the pyritic gneiss, but hematite also is abundant in the Potsdam at places where the Potsdam fills valleys that were of lower elevation than the pyritic ridge.

The hematite is predominantly earthy red but includes a large amount of the blue compact variety, and minor amounts of specularite. Chlorite is a typical associate of the hematite. Even granite masses, intrusive into the gneiss, were completely chloritized, and the pyritic gneiss is described frequently as a chlorite schist. Some of the chlorite in this gneiss is hydrothermal, but much is supergene, the two varieties being distinctive. This interpretation was reached by Smyth in 1894, by Buddington in 1917 and later,[8] and is concurred in by the writer. Some of the

[8] Smyth, C. H. Jr.: On a basic Rock Derived from Granite. Jour. Geol., vol. II, pp. 667–679, 1894. Buddington, A. F.: Buddington's views are not clearly expressed in print but are summarized in the following quotation from a personal letter in 1933.

"The chlorite accompanying the sulphide (pyrite and pyrrhotite) mineralization I follow Smyth in interpreting as formed at the same epoch as sulphides. The chlorite accompanying hematite was similarly formed at same epoch as hematite. . . . I found chlorite replacing granite in St. Lawrence County without associated sulphides, and also the chlorite and hematite seemed to go together whether sulphides were within one foot or 500 feet. My conclusion was that there were two ages of chloritization, one hydrothermal restricted to pyritic zones, the other supergene associated with hematite."

limestone and even of the Potsdam is likewise altered to dark green chlorite similar to that at Balmat, and presumably supergene.

Deep Oxidation in Ontario.—Oxidation and supergene enrichment are not common features of the known ore deposits of the Canadian shield, and the conclusion has generally been that they are incompatible with the geological history of the region. Nevertheless, enough evidence has been cited to show that in favorable limestone areas ground-water has circulated to depths of more than 1000 feet and has produced substantial oxidation to depths of several hundred feet wherever it encountered material suitable for oxidation. As a final illustration, the instance of the Keely Silver mine [9] at Cobalt, Ontario, is worth mentioning. Extensive oxidation and secondary enrichment to a depth of more than 560 feet in a narrow vein has been fully demonstrated in that instance.

OCCURRENCE OF SECONDARY MINERALS.

General Features.—Balmat mill heads in 1933 consisted, by volume, of about one-third sulphides, one-third limestone (carbonate), and one-third silicates with minor quartz. The sulphides included about 16 per cent. each of sphalerite and pyrite and one per cent. of galena. Approximately one-fourth of the sphalerite and galena is secondary, and the gangue includes about 2 per cent. of chlorite, 2 per cent. of iron oxide, chiefly hematite but in part magnetite, and traces of ilvaite, all attributable to the same processes that formed the secondary sulphides. Although this condition has been at a maximum in the early life of the mine, it promises to be of importance for several years.

The occurrence of secondary sulphides at Balmat may be summarized as follows. Sphalerite occurs plentifully in three ways:

1. As a more or less complete replacement of pyrite grains. In this case it is generally strongly colored by the associated hematite or magnetite and is recognizable only under the microscope.

2. As a replacement or reworking of primary sphalerite.

[9] Bell, J. Mackintosh: Deep-seated Oxidation and Secondary Enrichment at the Keely Silver Mine. ECON. GEOL., vol. 18, pp. 684–694, 1923.

3. Replacing gangue, chiefly barite, talc, chlorite and carbonate. In the last two cases its color is various shades of white or light yellow and although it is not conspicuous, it is often recognizable by eye. The light color is generally a ready means of distinguishing the secondary from the primary sphalerite, which is dark brown. The distinction is much more apparent in thin sections than to the unaided eye. The manner of occurrence, however, is the basis on which the relative ages and origin are established. The secondary sphalerite, accompanied by hematite and magnetite, replaces pyrite with preservation of the pyrite form; it also replaces barite and talc, minerals which are later than the primary sphalerite, often preserving the barite form; and it replaces chlorite, a secondary mineral.

Secondary galena in minor amounts accompanies that part of the sphalerite which replaces pyrite, constituting an inner fringe around the pyrite remnants, a habit totally different from that of primary galena. A little secondary galena replaces primary sphalerite along cracks and cleavages, and in rare instances it replaces chloritic gangue. Characteristic habits of the most important secondary minerals are illustrated in Fig. 1.

FIG. 1. Microscopic relations of secondary minerals at Balmat.

A. Five grains of pyrite almost completely replaced by secondary sphalerite with associated magnetite and hematite. *P*, pyrite remnants; *SS*, Secondary sphalerite (*a*) colored red by earthy hematite, (*b*) black with finely disseminated magnetite. Clear areas replace gangue and primary sphalerite. Thin section. × 5.

B. Primary sphalerite (*S*) and pyrite (*P*) slightly attacked by secondary sphalerite (*SS*) and secondary galena (*G*). Thin section. × 18.

C. Secondary sphalerite (*SS*), galena (*G*) and chalcopyrite (*CP*) replacing pyrite (*P*). Polished section. × 18.

D. Secondary sphalerite (*SS*) with contemporaneous magnetite crystals (*M*) replacing pyrite (*P*). Secondary galena (*G*) has replaced secondary sphalerite along contact with pyrite but has surrounded the magnetite without replacement. Polished section. × 70.

E. Secondary sphalerite (*SS*) replacing barite (*B*), with preservation of some tabular barite shapes. Thin section. × 18.

F. Willemite (*W*) replacing talc, which later was mildly chloritized (*TC*). Willemite molded around tremolite (*T*). Typical crystal forms of willemite, and aggregates with talc or chlorite centers. Thin sections. × 18.

Chlorite.—The main features of the distribution of chlorite and related oxidation products at Balmat are shown in Fig. 2. Chlorite is most abundant at the southwest end of the mine, gradually fading to the northeast and, according to drill hole in-

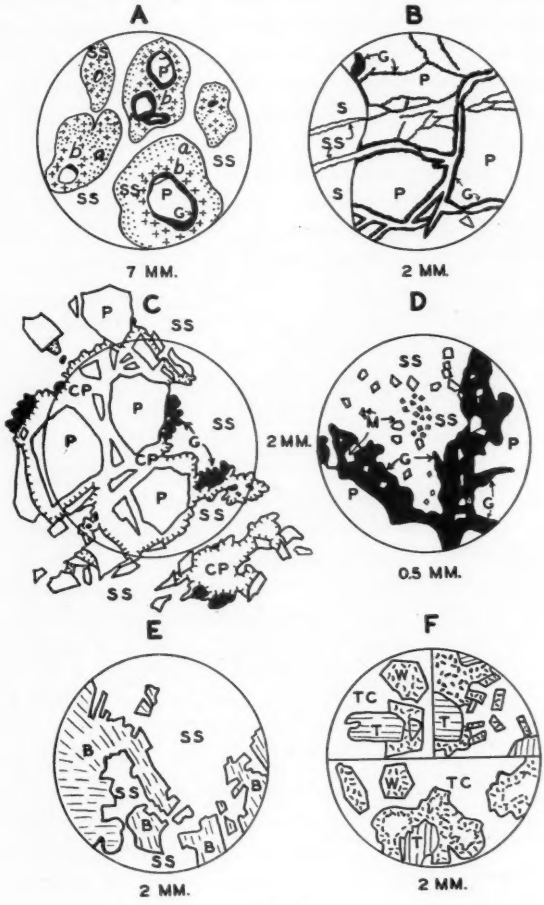

FIG. 1.

formation, also fading in depth, the decrease occurring principally between 700 feet and 1000 feet. In areas of strong chloritization, as exposed above the 500-foot mine level, it is common for all waste and gangue within the ore except quartz to be thoroughly chloritized, and the ore bodies are enclosed in an envelope of chlorite. The most highly chloritized rock is dark green or nearly black, but many shades of lighter green represent milder alteration. The chlorite is of fine texture, almost never visibly crystalline. Chloritization generally affects the walls for a distance of one foot to 10 feet, decreasing in intensity outward. Hematite almost always accompanies the chlorite in an irregularly streaked and spotted fashion. There is a pronounced tendency for chlorite to be more characteristic of the footwall of a given vein or of the footwall vein where there are parallel ore shoots.

The chlorite is an alteration product of diopside and talc, and to some extent of tremolite, and is believed to have been formed by solutions high in ferrous iron derived from the oxidizing ore bodies. It develops along cracks and cleavages in diopside or tremolite, much like the formation of talc at an earlier stage. Much of it appears to be a conversion of talc, the principal change being the addition of ferrous iron, with a corresponding development of green color. Owing to transfer of material in solution, much chlorite has formed outside the limits of its parent minerals as a replacement of carbonate and barite. In replacing these minerals and talc, ringed or concentric colloform structures are common, possibly suggestive of deposition from colloidal solutions. Diversely oriented slickensiding is characteristic of strongly chloritized areas, apparently due to increase of volume.

Chlorite fills cracks in primary sulphides. As a rule it preceded the secondary sulphides which, to some extent, replace it.

Hematite.—The distribution of hematite in the Balmat mine (Fig. 2), corresponds closely to that of chlorite, but its intense development covers a smaller area and is more patchy and localized. On the other hand, traces of hematite as a slight stain on limestone country rock are much more widespread than chlorite.

Within the most intensely oxidized area (Fig. 2) patches of

"paint rock" or "paint ore" are common admixtures with the sulphides, both primary and secondary. Hematite also forms highly colored bands and areas in the chlorite along the walls but is notably more prominent in the hanging wall, just as chlorite is typical of the footwall. It is likewise most abundant in the upper levels, with an irregular but progressive decrease in depth. One very productive stope above the 300-foot level was commonly known as the "red raise" and had much the appearance of a soft hematite mine. This stope, with a production of some

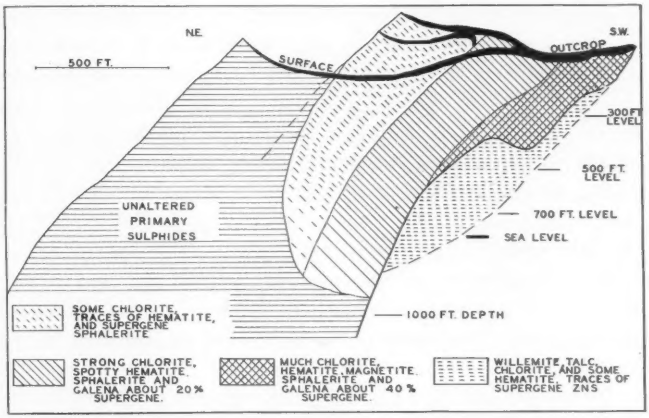
NE.
S.W.
500 FT.
SURFACE
OUTCROP
300 FT. LEVEL
500 FT. LEVEL
700 FT. LEVEL
SEA LEVEL
1000 FT. DEPTH
UNALTERED PRIMARY SULPHIDES
SOME CHLORITE, TRACES OF HEMATITE, AND SUPERGENE SPHALERITE
STRONG CHLORITE, SPOTTY HEMATITE, SPHALERITE AND GALENA ABOUT 20% SUPERGENE.
MUCH CHLORITE, HEMATITE, MAGNETITE, SPHALERITE AND GALENA ABOUT 40% SUPERGENE.
WILLEMITE, TALC, CHLORITE, AND SOME HEMATITE, TRACES OF SUPERGENE ZNS

FIG. 2. Occurrence of secondary minerals at Balmat mine. Southwest ore body projected on plane of vein.

20,000 tons, constituted the largest body of intensely oxidized ore in the mine. Within it almost all pyrite was completely oxidized and the proportion of secondary oxides and sulphides was extreme. The ore body in this area, raking strongly northeast, terminates downward along a pointed keel. Along this keel paint rock is abundant and in places continues down along the extension of the ore-bearing structure, far into the willemite zone.

Probably 90 per cent. of the hematite at Balmat is of the red earthy variety and occurs as an incomplete replacement or im-

pregnation of other minerals, especially pyrite, chlorite and talc, carbonate and barite. The hematite fills fractures in silicates and extensively replaces garnet. In replacing talc and chlorite, development of ringed and concentric structures is common although not always readily distinguished from similar structures pseudomorphic after pyrite. In either case the banded structures generally exhibit alterations of red earthy and dark compact hematite, as well as simple variations in intensity of earthy hematite.

Specularite, probably constituting less than one per cent. of the total hematite, occurs as tiny crystals occasionally visible to the eye and from 0.1 to 0.5 mm. in length. They replace almost any gangue minerals, including the pre-ore silicates, but seem to be especially abundant in barite. They also rarely replace pyrite. A radial distribution pointing outward around some nucleus, such as a pyrite crystal, or radiating from a concentric structure in hematite, is common. All the microscopic features seem to indicate the formation of specularite at a late stage in the oxidation process.

Minute flakes of specularite, visible only at magnifications of 350 to 500 diameters, are also abundant: (1) Impregnating secondary sphalerite that replaces pyrite, which is in association with more abundant non-crystalline hematite; (2) Included in garnet that has been heavily hematized, chiefly by the earthy variety; (3) Included in ilvaite; (4) Along cleavages or cracks in primary sphalerite where oxidation is incipient.

Ilvaite.—Ilvaite occurs as glistening black crystals not exceeding 2 to 3 mm. in length. The usual form is a prism of four sides, smooth and unstriated, giving trapezoidal or diamond-shaped cross sections. In addition to the visible crystals there is much fine-grained aggregated material.

A very satisfactory analysis was obtained on crystals of excellent purity, broken cleanly from an inclosing matrix.

ANALYSIS OF BALMAT ILVAITE.

CaO	MgO	Al_2O_3	SiO_2	FeO	Fe_2O_3	MnO	H_2O	Total
13.78	1.77	0.17	29.00	31.42	17.98	3.96	1.49	99.57

Assuming that manganese substitutes for ferrous iron, and magnesia for lime, this corresponds closely to the formula:— $H_2O.3CaO.5FeO.Fe_2O_3.5SiO_2$,—a slight variation from Dana.

Evidence that ilvaite belongs to the secondary period is as follows: It is found only in areas of darkest and most intense chloritization; it definitely replaces barite, a post-sulphide primary mineral.

In rare cases colloform intergrowths of hematite and ilvaite have been observed, but more commonly they are mutually exclusive, suggesting that where ilvaite developed it accomodated all the ferric iron.

Magnetite occurs only in the most intensely oxidized areas, chiefly at the southwestern tip of the ore body, and as a general rule it is restricted to the physical limits of former pyrite grains. Highly magnetic ore has a dull black color and a fine-grained, cryptocrystalline appearance. It shows many roundish knots ⅛ to ¼ inch in diameter representing replaced pyrite grains, with small "eyes" of pyrite usually visible. The purest material that can be selected by fine grinding (200 mesh) and separated by a hand magnet under water does not exceed 25 per cent. magnetite, and will invariably assay 30 to 40 per cent. Zn. When first encountered it was suspected of being franklinite, but chemical, microscopic and x-ray investigations all show that it is very finely divided magnetite in a matrix of sphalerite.

The magnetite is best studied in polished section by oil immersion at magnifications of 500 diameters or more. This brings out the clouds of tiny crystals, specks, and aggregated areas in the secondary sphalerite, and shows many of the larger magnetite specks (0.1 mm.) to be very perfect octahedral crystals (Fig. 1, *D*). These larger crystals may exhibit a tiny core or nucleus, apparently of unreplaced pyrite.

Secondary Sphalerite.—The main features of the distribution of secondary sphalerite are given in Fig. 2. As with magnetite, its occurrence seems to be governed by a rather definite law. It is restricted either to the physical limits of original primary sulphide ore bodies, or their immediate vicinity. The limiting distance is generally a few feet.

Secondary sphalerite occurs almost entirely in small grains, not exceeding 0.1 mm. Its color is white or light yellow, and in thin section it is notably transparent, in contrast to primary sulphide. Owing to its intimate association with more effective pigments such as magnetite, hematite and chlorite, and because of the small size of its grains, it is inconspicuous to the eye, and its importance would not be suspected by a casual observer. Familiarity with its microscopic characters enables one to recognize it with fair accuracy underground. The problem is not usually of much importance, since the limits of mining are defined by remnants of primary ore and of associated magnetite and "paint rock." The several modes of occurrence of secondary sphalerite may be described in order.

About one-third of the secondary sphalerite replaces pyrite. As a rule the attack began around the perimeter of a grain and worked inward rather evenly. As it proceeded a network of cracks occupied by sphalerite generally developed throughout the pyrite, and gradually expanded coincident with the marginal replacement. All stages of the process can be illustrated by readily available specimens. The sphalerite usually shows distinct crystallinity (cleavage pattern), but quite fine-grained and in numerous cases distinctly finer-grained in the last interior remnants, which may appear dull white and "amorphous," suggesting that replacement proceeded more and more slowly toward the interior.

With rare exceptions the sphalerite includes a considerable amount of magnetite or hematite or both (Fig. 1, *A*). These are arranged in concentric zones alternating with each other and varying greatly in intensity, the outer band generally being strongly clouded, commonly with hematite. The bulk of the hematite occurs as an earthy red stain but some of it consists of minute specularite flakes arranged in concentric bands, or of irregular lines and patches so arranged. The earthy hematite, the specularite, and the magnetite are to a considerable degree mutually exclusive, each occupying its own distinctive zones or streaks. These various features, in the writer's opinion, indicate that the hematite and magnetite were deposited contemporaneously with the sphalerite and are not of later introduction.

Another one-third of the secondary sphalerite replaces primary brown sphalerite, which, in the oxidized areas, is abundantly seamed and fringed by the later generation. To some extent this may not be strictly replacement but a conversion, in place, of the brown sphalerite into the light variety. There are all stages of transition through yellowish-brown and brownish-yellow with apparent preservation of the crystal structure (cleavage pattern). This suggests that the oxidizing solutions may simply have bleached the brown sphalerite by removing the iron. On the other hand, actual pseudomorphous replacement may have occurred.

The remainder of the secondary sphalerite replaces gangue interstitial to ordinary primary sulphides, and extends for limited distances into the walls, especially the chloritized footwall. It replaced chiefly barite, talc and chlorite, but also carbonate, where any was available, and to a slight extent silicates, particularly garnet. In replacing barite it sometimes exhibits elongated and bladed shapes, evidently pseudomorphous (Fig. 1, *E*). In rarer cases it shows some of the colloform and concentric forms of chlorite. Oölitic granules formed by the replacement of a film of talc around small pyrite grains have been noted.

Crystallinity is much more distinct in this type of sphalerite than in that which replaces pyrite, and cleavage faces up to 0.1 mm. across are common. The color of the sphalerite is white to light yellow. In many cases it is moderately stained along cleavages by earthy hematite, and in some instances is strongly replaced by it. Specularite crystals commonly are embedded in the sphalerite, probably as a result of replacement.

In rare instances sphalerite crystals up to ¼ inch in diameter have been found coating barite and coating or replacing talc-chlorite in cavities which seem to be due to leaching by the same solutions which produced hematite and chlorite. The smaller crystals are yellow, the larger ones usually light, clear brown, all transparent in thin section; the larger ones are zoned and darker on the exterior. The relations to barite and chlorite and the absence of inclusions of chalcopyrite-pyrrhotite, typical of pri-

mary ore, suggest that these crystals are secondary and not primary. The volume of such sphalerite is insignificant.

Secondary Galena.—Secondary galena is plentiful in the most intensely oxidized part of the Balmat deposit (Fig. 2) and in localized spots, chiefly along the footwall, in the zone of intermediate oxidation. Since the amount of primary galena is small compared to that of sphalerite, the quantity of secondary galena is relatively small. Nevertheless, there are stopes which have averaged about 2 per cent. Pb, chiefly secondary, and within these stopes small areas containing 5 per cent. or more. The secondary galena can be identified only by the microscope, since it is very finely divided and is masked by more abundant dark-colored associates.

There is only one occurrence of this type of galena that has economic importance, namely, in association with much more abundant secondary sphalerite, where the latter replaces pyrite (Fig. 1, *A* to *D*). The galena forms the inner ragged fringe around the unreplaced pyrite remnants. Also, the last narrow cracks that developed in the pyrite as it split up under oxidation commonly contain only galena. In rare cases where secondary sphalerite had not previously attacked the pyrite, replacement by galena began directly at the outer margin and extended inward along the initial network of cracks.

For the most part it would appear that secondary galena did not actually replace pyrite, but replaced secondary sphalerite where it was in contact with pyrite (Fig. 1, *D*), and the same is true of chalcopyrite. Evidence of this is afforded by the ragged inclusions of secondary sphalerite within the chalcopyrite and galena, and especially by the relations of magnetite crystals included in galena (Fig. 1, *D*). These have a habit and pattern indicating that they were formed along with secondary sphalerite which has now been replaced from around them by galena. In other cases, however, magnetite was replaced by galena, and apparently always by chalcopyrite.

Of mineralogical interest is a single observed instance of secondary galena replacing gangue. A specimen of dark chloritic

rock from the foot-wall shows an abundance of finely divided galena, which is pseudomorphous after circular and colloform structures in chlorite.

In two cases, crystals of galena have been found coating barite in vugs associated with secondary sphalerite.

The period of deposition of secondary galena evidently succeeded that of sphalerite, although Schürmann's law suggests that it should come earlier. Two factors doubtless contributed to this condition. First, sphalerite is many times more soluble than galena in oxidizing waters, and second, the amount of primary galena compared to that of sphalerite is less than 1 to 10. The solutions that penetrated the ore deposit, therefore, at first dissolved chiefly zinc; it was only later and much more slowly that they attained an appreciable concentration in lead.

Secondary Chalcopyrite.—In almost all cases secondary chalcopyrite accompanies and is more or less intergrown with galena, generally in narrow cracks between unreplaced pyrite remnants, the whole surrounded by secondary sphalerite. There is much secondary galena which is not accompanied by chalcopyrite, and no stope would assay more than a small fraction of a per cent. of copper. In the clearest cases it seems that chalcopyrite preceded galena (Fig. 1).

Since copper is one of the most mobile of metals under oxidizing conditions and one of the first to be deposited in supergene forms, it seems anomalous at first to find it deposited after sphalerite. The explanation doubtless is much the same as that offered for galena. The amount of copper in the primary ore is minute, and occurs wholly as small inclusions of chalcopyrite in primary sphalerite. It follows that the copper in solution became appreciable only after zinc had been dissolved in great quantity.

Willemite.—The distribution of willemite, known as yet only in its broad outlines, is shown in Fig. 2. Its occurrence again may be formulated into a rather definite rule. Willemite is found only outside the limits of primary sulphides and chiefly beneath areas of most intense oxidation.

Willemite ($ZnSiO_4$) is famous mineralogically as one of the

chief ore minerals in the unique deposits at Franklin, N. J., where it is commonly, and doubtless correctly, regarded as a primary mineral formed at high temperature. It is considered a rare mineral elsewhere, but has been reported from some districts under circumstances strongly suggesting its supergene origin. Thus Lindgren [10] states that "willemite may be formed during oxidation, as at Tres Hermanas, New Mexico, and Pioche, Nevada." There are also a number of African occurrences for which the brief published descriptions strongly suggest, in the writer's opinion, a supergene origin in connection with the oxidation of sulphide ores.[11] That at Broken Hill, Northern Rhodesia, seems to be the most important. Willemite at Moresnet, Belgium, is generally conceded to be supergene, and supergene willemite in Mexico has been described recently by Foshag.[12]

Willemite at Balmat was first identified in a diamond-drill core that penetrated the ore zone near its southwestern margin at a vertical depth of approximately 600 feet. Later a band of similar rock was cross-cut on the 500-foot level, southwest of the limits of sulphide ore. Systematic sampling of the walls revealed a zone 10 or 15 feet wide averaging about 15 per cent. Zn, as willemite. Samples were then taken of all the suspicious bands on the 300-foot level, and although numerous assays were negative, three separate narrow zones showed 8 to 30 per cent. Zn as willemite, all in suggestive position beneath the most intensely oxidized sulphide ore. It is difficult, however, to distinguish by eye the willemite-bearing zones from similar rock containing no zinc.

The willemite occurs in a soft, green, talcy-chloritic rock generally moderately stained by hematite. It is glassy, transparent, and shows in thin sections as: (1) well formed crystals, 0.2 to 0.5 mm. in dimension, showing hexagonal cross-sections and prismatic forms; (2) irregular aggregates of formless grains; (3)

[10] *Op. cit.*, p. 851.

[11] Spencer, L. J.: South African Occurrences of Willemite, Fluorescence of Willemite and Some Other Zinc Minerals in Ultra-Violet Rays. Miner. Mag., vol. 21, no. 119, pp. 388–396, 1927.

[12] Foshag, Wm. F.: Ore Deposits of Los Lamentos, Chihuahua, Mexico. Econ. Geol., vol. 29, pp. 330–345, 1934.

radial or fibrous forms with the centers generally occupied by irregular areas of chlorite.

Each type is plentiful. The habits of occurrence are illustrated in Fig. 1, *F*. In rare cases the hexagonal crystals are visible to the eye as vitreous spots in the green matrix.

The mineral relations as observed in thin section suggest that willemite and chlorite developed very nearly together. The willemite replaced especially talc (or mildly chloritized talc), but also barite, carbonate, and possibly chlorite. It is molded around tremolite, which it did not replace, and rarely around garnet, but generally replaced the latter, more slowly, however, than talc and other minerals. Some chloritization probably followed the willemite, and the chlorite centers in radial forms may represent chloritization of original talcy centers, or else contemporaneous development of chlorite and willemite. Hematite followed willemite and chlorite, and penetrated the willemite along cracks and cleavages, but with little or no replacement. Willemite has nowhere been found microscopically in contact with sulphides, either primary or secondary.

The information available is not yet sufficient to afford any accurate basis for estimating the amount of willemite, but suggests that there may well be 100,000 tons or more of material assaying 10 to 20 per cent. Zn. Whether this can ever be used commercially is uncertain.

Other Secondary Products.—It is possible that other minerals, in addition to those described, belong to the later epoch of mineralization. If so, the criteria for recognition of the secondary fractions have not been developed. The most important mineral that might possibly be secondary to a considerable degree is talc, but no proof of this has been found, and most of the talc is almost certainly of the hydrothermal period. Particular search was made for secondary iron sulphide, either pyrite or marcasite, but none was found.

DATE OF OXIDATION.

The oxidation of the Balmat ore-body is definitely pre-glacial. Glacially transported boulders of zinc ore, both oxidized and

unoxidized, have been found which resemble these respective types of ore in place and which show no evidence of appreciable oxidation at their present location. Again, fresh surfaces of unoxidized primary ore have been uncovered beneath only a few inches of glacial soil. The sink holes of the region, which are believed to have been formed contemporaneously with the oxidation, are filled with drift.

Whether the oxidation is pre-Cambrian or post-Cambrian is less certain. Buddington prefers the view that most of the oxidation at the hematite mines was pre-Cambrian with slight post-Cambrian additions. The writer's own review of this matter leads him to believe that the oxidation is mainly post-Potsdam. The following points are cited:

1. Petrographic study shows that hematite and secondary quartz have replaced the matrix of the Potsdam sandstone extensively.

2. The galena-calcite veins of the vicinity, which in some instances cut Potsdam sandstone, almost invariably show considerable oxidation of pyrite and sphalerite near the surface.

SUMMARY.

The evidence given, and many details that cannot be included, convince the author that the sequence of secondary minerals described is supergene and was formed by ordinary ground water. Since some skepticism regarding this conclusion has been expressed, it may be added that in the beginning he followed the natural inclination of most geologists schooled in modern magmatic theories and tried to establish a second period of primary mineralization. The more the evidence accumulated, the less it seemed to fit this interpretation.

The crux of the problem is this: Does soft earthy hematite occurring in thousands of tons in the vicinity of a pyritic ore body which it has obviously replaced, and occurring most abundantly at the surface, decreasing and disappearing at a depth which, although surprising, is still relatively superficial, imply oxidation by surface waters? The writer believes that it does.

If so, the rest of the argument is inescapable. Microscopic study shows that the minor amounts of specularite, magnetite and ilvaite are contemporaneous with the hematite, and that the second generation of sulphides is related and contemporaneous.

Certain features of the evidence will bear reiteration. The tendency for hematite to characterize the hanging wall and chlorite the footwall is pronounced. This seems clearly related to field evidence that descending waters commonly reached the ore body by way of joints in the hanging wall and then either passed through it or traveled downward along its surface. Freshly laden with oxygen, they attacked the ore and formed abundant hematite along its upper surface, and at points beneath the raking keel. That part of the solutions which penetrated the ore body and reached the footwall was, as a rule, reduced by the sulphides to the ferrous state, and so formed mainly chlorite.

The abundance of colloform structures, the centripetal replacement of pyrite or its destruction along crystallographic planes, and the prevailing fine-grained character of the secondary minerals, deserve emphasis, for these features are commonly accepted as evidence of deposition at low temperature or from cold waters. The fine-grained character is significant, especially with regard to specularite, magnetite, and ilvaite, minerals that some would assert are proof of high-temperature magmatic origin. Nevertheless good authorities have attested the formation of both specularite and magnetite as supergene products. Lindgren [13] can be quoted as follows: "It is known of course that hematite and even crystallized specularite may develop in oxidized ores and in laterite . . ." Emmons has described magnetite in minute specks as an oxidation product.[14] Hallimond and Cayeux have determined magnetite in the unaltered sea-floor ironstone of Britain and France.[15] The existing knowledge re-

[13] Lindgren, W.: The Silver Mine at Colquijirca, Peru. ECON. GEOL., vol. 30, p. 343, 1935.

[14] Emmons, W. H.: U. S. Geol. Survey, Bull. 529, pp. 146–147.

[15] Hallimond, A. F.: Memoir Geol. Survey of Gt. Britain, Spec. Rep., vol. XXIX, pp. 25–26, 75–76, 1925. Cayeux, L.: Les Minerais de Fer Oölithique, vol. II, pp. 306–321, 384–392, 1922.

garding ilvaite is too meager to permit generalization. All these minerals occur at Balmat either in uncrystallized aggregates or in crystals that are generally of microscopic size. The same is true of chlorite, and much of the secondary sphalerite is amorphous in appearance (not actually), although some is distinctly crystalline.

Another argument advanced against the supergene interpretation is that the region of northern New York and Southern Ontario is the locus of a widespread post-Cambrian magmatic mineralization typified by fissure veins filled with calcite and accessory pyrite, sphalerite, galena, barite and traces of fluorite.[16] It is plausible to suggest that the second generation of sphalerite, galena and associated hematite and magnetite at Balmat are related to this second primary mineralization. The writer has examined many of the veins of this later age in New York and Ontario and believes the differences between them and the Balmat occurrence are so consistent and fundamental that no one familiar with the two types would suggest a correlation. This has been the conclusion of several geologists who have actually examined them.[17]

In the study of this problem three expressions of mineralization require comparison; (1) the post-Cambrian fissures filled by calcite and minor sulphides, (2) the hematite mines, which exhibit earthy hematite, minor specularite and abundant chlorite significantly related to certain pyritic strata, (3) the Balmat secondary mineralization, dominated by hematite, chlorite, and secondary sulphides, as herein described. The most cursory examination should suffice to show that the last two are closely related to each other and unrelated to the first.

[16] Alcock, F. J.: Zinc and Lead Deposits of Canada. Geol. Survey of Canada, Econ. Geol. Ser. No. 8, 1930. Smyth, C. H. Jr.: The Rossie Lead Veins, St. Lawrence Co., N. Y. Columbia Sch. Mines Quart., vol. 24, pp. 421–429, 1903.

[17] The upper portions of these fissure veins almost invariably show solution of calcite and oxidation of sulphides, but according to a pattern distinct from Balmat. The sulphides are seldom in contact and the matrix is usually 80 per cent. or more calcite. The result is respectively limonite (in rare cases hematite) from pyrite, limonite with smithsonite from sphalerite, and anglesite from galena.

If the supergene interpretation at Balmat is correct, certain aspects of it are worth noting. In and near the primary sulphides, secondary deposition of zinc, lead, or copper took the form of sulphide regardless of the material replaced. Evidently the solutions pervading the ore body were dominated by some reagent or condition which demanded the precipitation of sulphides to the exclusion of anything else. It seems obvious that, in some way or other, the controlling factor was the high sulphur content of the primary ore.

Magnetite as an associate of supergene sphalerite and hematite in the replacement of pyrite seems to imply some obscure, mildly reducing condition, perhaps also related to the sulphide influence.

Willemite was the typical product of the large excess of zinc solutions which was unable to become fixed in the vicinity of the primary sulphides and migrated down into the wall rock along the keel of the ore body. Here it seems that the influence of the sulphides was lost and that of silica became predominant. This was doubtless due to the large amount of silica in the wall rock, especially in the relatively loosely bound form of talc. In fact, although the country rock of the region is, in general terms, a metamorphosed limestone, the intimate gangue consists mainly of silicates, and these rather than the small carbonate content have given character to the entire process of alteration. The apparent absence of smithsonite and calamine, and the virtual absence of "limonite," all of which are the more usual products of the oxidation of zinc ores, is noteworthy. Their place is taken by willemite, the anhydrous silicate of zinc, and by hematite, the similarly anhydrous oxide of iron. Note, however, that the willemite occurs only as small crystals or aggregates in a soft, decomposed matrix of hematite, chlorite, and talc that crumbles in the fingers, not in the firm condition nor with the unaltered silicate association that should accompany a primary mineralization. Also, the hematite is the soft earthy variety, full of colloform and concentric structures, that is typical of weathering. This, and not its association with small quantities of microscopic specularite and magnetite, is the significant feature.

A suggested reason for the formation of the anhydrous oxidation products is that they were precipitated below the water table, in the absence of free air and its associated oxygen, and that the region was of such low relief that circulation was very slow and deposition occupied an unusually long time. Indeed, the effects described in this paper are believed to represent almost altogether the deeper part of the zone of oxidation, below the water table. No doubt there once existed at higher levels a zone of sulphide impoverishment which has been removed by glacial and pre-glacial erosion except for suggestive remnants such as the Dominion prospect.

The writer would summarize his idea of the conditions which led to this rather unusual case of oxidation and secondary enrichment as follows:

1. Abundant pyrite well distributed through the ore.
2. Ore locally more porous than wall rock, and dipping steeply enough to confine the solutions in or near it for long distances.
3. Very slow circulation and an unusually long time-interval.
4. Deposition below the water table.
5. For cold solutions, an unusual concentration of metallic salts.

ST. JOSEPH LEAD COMPANY,
EDWARDS, N. Y.,
Nov. 22, 1935.

ASBESTOS DEPOSITS OF THETFORD DISTRICT, QUEBEC.[1]

H. C. COOKE.

THE work on which the present paper is based has been carried on by the Geological Survey of Canada for the last six field seasons, 1930 to 1935 inclusive. All of this time, however, has not been spent in studying the asbestos deposits. During the period an area of about 1,000 square miles has been mapped in detail, and this gives a fairly sound conception of the geological history of the region and its general structure. This general study has materially assisted in correcting earlier erroneous opinions as to the structural relations of the serpentines and associated rocks, and has resulted in some interesting conclusions.

GENERAL GEOLOGY AND STRUCTURE.

The geology of the Thetford-Black Lake area is shown in Fig. 1. The basal rocks, here termed Caldwell series, are quartzites, slates, and lavas, probably of Cambrian age. J. A. Dresser referred to them as the L'Islet quartzites and the Sillery slates, thus correlating them with somewhat similar rocks near Quebec. The only recognizable horizon marker among these rocks is the lava (Fig. 1). A mile or two northwest of Thetford this series is highly metamorphosed to sericitic and chloritic schists, and this petrographic difference caused earlier workers, and myself at the commencement of my work, to class the schists as pre-Cambrian. It is now thoroughly established, however, that no determinable break occurs between the schistose and non-schistose rocks, and accordingly, they are all classed together under the name Caldwell

[1] Presented before the Society of Economic Geologists, New York meeting, Dec. 29, 1935.

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series. On the southeast the Caldwell series is overlain unconformably by black slates with a thin basal conglomerate. These rocks are termed the Beauceville series, and fossils indicate their age as Ordovician.

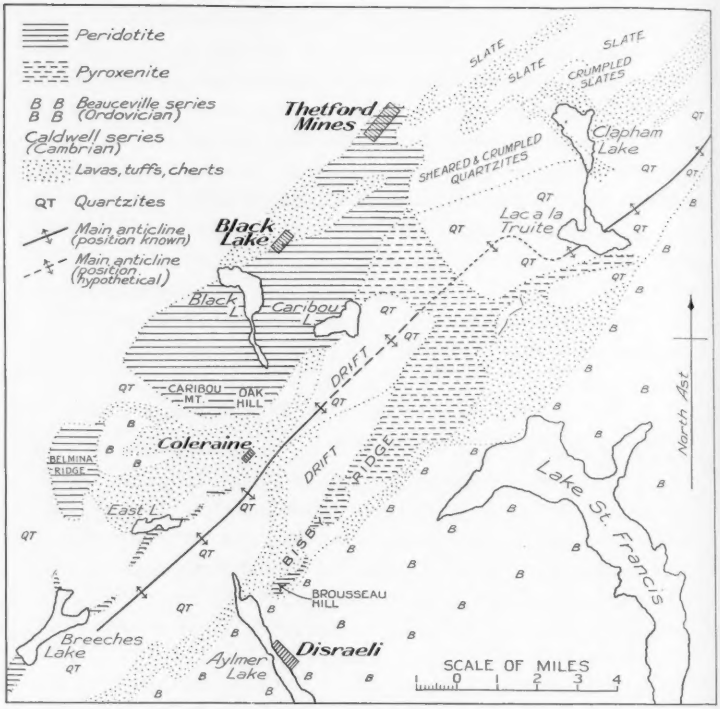

FIG. 1. Main features of the geology of the Thetford-Disraeli district, Quebec.

All the sedimentary rocks are closely folded along northeast axes, and for the most part have nearly vertical dips. The main anticlinal axis of the region follows roughly the center of the band of schist northwest of Thetford. From this axis the gen-

eral dip is southeast, although subordinate folds are numerous, as far as the center of the slate area north of Clapham Lake (Fig. 1). Beyond this, the general dip is northwest as far as the second main anticlinal axis of the region (Fig. 1). The northeast strike of the strata is uniformly maintained over large areas, except near the ultrabasic intrusives, where there are certain disturbances that will presently be mentioned.

The intrusive rocks of the region are peridotite, pyroxenite, and gabbro. All of these were formerly considered differentiates of a common magma, but the gabbro has now been proved to be older than the peridotite and its pyroxenite derivatives.[2]

The disturbances of the structure near the peridotite masses are numerous, and have been made the subject of a separate paper.[3] (1) The strata around Clapham Lake have been intensely crumpled and sheared. (2) The general strike of the beds around Clapham lake is northwest instead of northeast, and the dip steeply northeast. (3) The strata west of Coleraine village are similarly disturbed and distorted, and dip southwest. (4) The lava horizon of the Caldwell series has been cut in two places by peridotite, and the broken ends apparently shoved aside. These disturbances and others point to the conclusion that the ultrabasic magma was thrust in from below like a gigantic punch, raising the strata directly above them, dragging upward the beds on the sides, and forcing to one side the rocks in the vicinity.

The peridotite with which the asbestos deposits are associated was composed originally of rather iron-poor olivine, with varying percentages of pyroxene and rare accessory chromite. The olivines average 3 to 4 mm. in diameter, with some up to 6 mm. and the pyroxenes as a rule are somewhat smaller. The pyroxenes are chiefly diallage, with some enstatite, and ordinarily constitute between 5 and 10 per cent. of the rock. They are mostly altered to bastite; the olivine crystals are fragmented by the customary anastomosing network of serpentine veinlets. Parts of the rock are completely converted into serpentine.

[2] Geol. Surv. of Canada, Sum. Rept. 1933, pt. D, pp. 123–128.

[3] Cooke, H. C.: The mode of Emplacement of the Thetford Peridotites and Pyroxenites. Trans. Roy. Soc. Can. (3), vol. 29, sec. IV, 1935.

Serpentinization has taken place in two stages, or at two different times. During the first stage there was a general serpentinization of the whole rock mass, whereby 40 to 60 per cent. of it was converted into serpentine. This alteration, as H. H. Hess has concluded, was probably caused by magmatic water. During the second stage, certain portions of the partly altered peridotite were converted completely into serpentine. These portions include sheared zones, the walls of faults, and the walls of joints. Obviously, the second serpentinization is caused by the entry of solutions through fractures.

THE ASBESTOS DEPOSITS.

Situation.—The asbestos deposits are all associated with peridotite masses, but are not scattered indiscriminately through them. On the contrary, the known deposits all occur fairly close to the northwestern borders of the peridotite. Any theory of origin must account for this peculiar distribution.

Relation to Faults.—The asbestos veins and deposits are all definitely related to faults, commonly to thrust faults. The results of a thrust fault were twofold. The drag of one wall on the other caused tension cracks to form, which run off from the fault plane at angles varying from 30 to 60 degrees, and at the same time induced a strained condition throughout the rock over widths of many feet. In many places this strain is manifested by the occurrence in the altered pyroxene crystals of little asbestos veins which end at the borders of the crystals (Fig. 2).

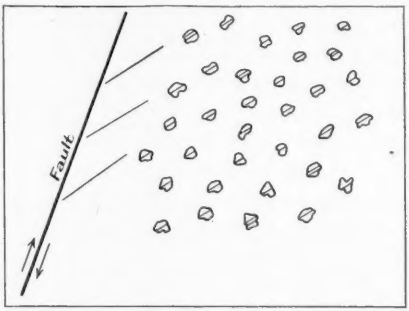

FIG. 2. Illustrates development of asbestos veinlets within bastite crystals, parallel to tension cracks of a neighboring fault.

All these veins are parallel to one another, or nearly so, within the zone placed under stress by a fault; they are also parallel to

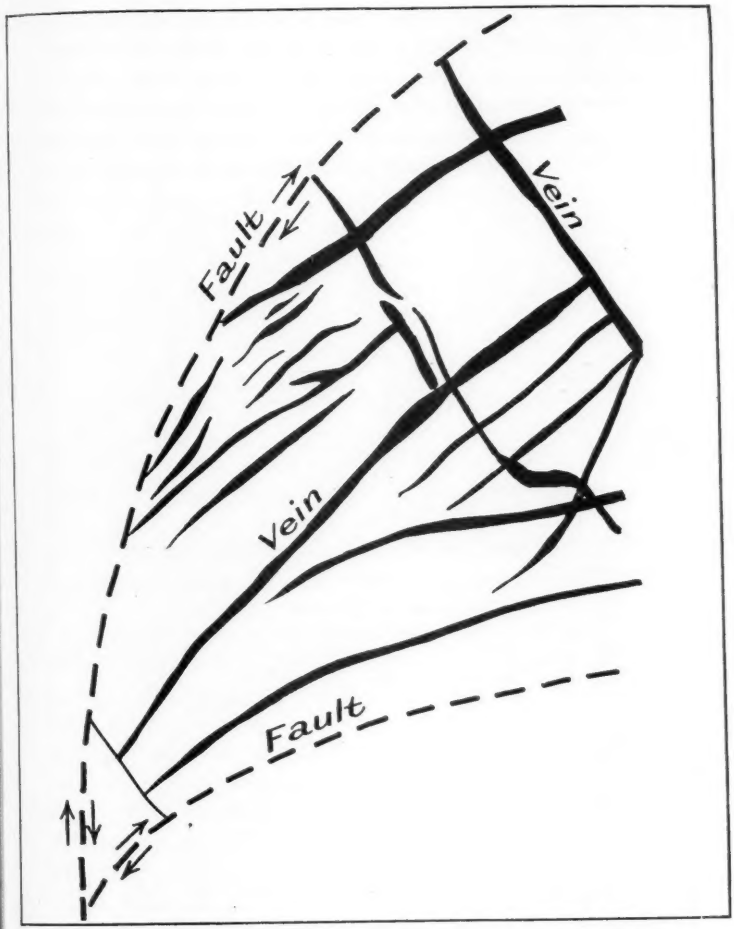

FIG. 3. Part of south face, Johnson pit, Thetford mines. Solid black areas are asbestos veins.

the tension cracks that branch off from the fault. There is no regional parallelism in these veinlets, however. A few feet away, in the zone of influence of another fault, the intra-pyroxene veinlets will display another orientation, parallel to the tension cracks of that fault. Under more intense strain, longer veins form. Figure 3 is a drawing of a part of the south face of the Johnson pit at Thetford Mines. The subparallel lenses of asbestos, closed at the ends, are characteristic. Where stresses have been still more severe, a regular vein system is developed. Figure 4 is a

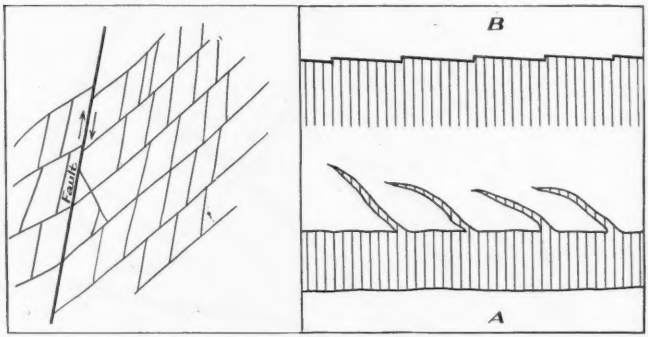

FIG. 4 (left). Part of north face, Johnson pit, illustrating regularity of vein system. The thin lines are asbestos veins.

FIG. 5 (right). *A*, tension cracks filled with fiber running off from a vein of type shown in Fig. 4. *B*, corrugated surface of a slab of fiber such as 5–*A*, when broken out of the rock.

rough sketch of a part of the north face of the Johnson pit, to illustrate how regular such a system may be.

In many veins, particularly in zones such as shown in Fig. 4, there has been a small differential movement of the walls, slickensiding them slightly and forming little tension cracks that run off a quarter of an inch or so into the walls (Fig. 5–*A*). These tension cracks are now filled with fiber, so that a slab of the main vein, when cobbed out, commonly has a corrugated

appearance (Fig. 5–*B*). Zones of this type make the best mining ground, because the percentage of fiber is large, and much of it is long.

The deposits as a whole are of three structural types. The simplest originate from a single fault, or a series of parallel faults with the same type of movement. In these the asbestos-rich ground forms a belt parallel to the fault and mainly on the footwall side, and the asbestos content decreases rather rapidly at a distance of perhaps 20 or 30 feet from the fault. It is obvious that faults must be fairly closely spaced to form a valuable deposit of this type. The best example of this type is a small deposit close to the highway at the southwest end of Black Lake village. The second type is that formed in blocks of ground bounded by faults that converge downwards. Lateral pressures accompanying the faulting caused great fracturing within such blocks, and thus gave rise to minable masses of asbestos. The large body of asbestos-bearing rock at Thetford Mines, on which the King, Johnson, and Bell mines lie, is of this type, as is also the Beaver mine. The third type is a block of ground bounded by thrust faults that converge upward. The Vimy Ridge mine, and the Johns-Manville deposit at Asbestos are of this type. All faulted ground does not contain asbestos, however. There are many known areas where the peridotites have been much broken by faults but which contain little or no asbestos.

Relations to Acid Intrusives.—There appears at first sight to be some sort of connection between the occurrence of asbestos and that of acid intrusives, locally termed "granite." Few of them are true granite, however. They seem to have consisted originally of albite to oligoclase albite, with or without some brown mica; most of them are much altered. At Thetford Mines, where the best quality of asbestos is found, dikes of this "granite" are numerous; at Black Lake, where the asbestos is somewhat harsher, dikes are on the whole somewhat fewer; at Vimy Ridge, where the asbestos is very harsh, dikes are few and small. The inference thus suggested is contradicted, however, by the existence of asbestos mines where there is no granite whatever,

and by the occurrence of granite dikes in many places where there is no asbestos. On the whole, the writer is inclined to believe that the occurrence of acid dikes has no direct influence on the occurrence of asbestos, but that the dike materials and the asbestos-forming waters may have had a common source.

Although there is not much direct evidence of the relative ages of the acid dykes and asbestos veins, studies recently completed indicate, by inference, that the dikes are the older. Both the dikes and the surrounding serpentinized peridotite, with included veins of asbestos, have been greatly altered. The alteration, which was complex, and took place in successive stages, cannot be described here; but it may be said that an important part of it was the development, in the dykes, of magnesian minerals such as tremolite and actinolite, while the surrounding serpentine was enriched in silica and alumina. Asbestos veins in the serpentine were similarly enriched, causing the fiber to become hard and brittle. These facts point to an interchange of materials between the dykes and surrounding rock, through the medium of circulating solutions; and as the only solutions known to have affected the peridotites were those forming the asbestos veins, it seems justified to conclude that they caused the alterations of the dykes.

THEORIES OF VEIN ORIGIN.

Three theories have been advanced to explain the origin of asbestos veins. (1) The veins are replacements; solutions entered along a tight crack which is now the central fissure, and recrystallized the adjacent serpentine to asbestos. (2) The veins are fissure fillings; open cracks were filled with fluid which either contained the components of serpentine in solution, or obtained them by dissolving part of the wall rock, and the dissolved material eventually crystallized as asbestos. (3) Taber's theory; solutions or vapors penetrated through the pores of the wall rock, extracted serpentine, and deposited it as asbestos in tight fissures. The growth of the fiber gradually pushed the walls apart sufficiently to form the existing veins.

Replacement Theory.—J. A. Dresser originally advanced the replacement theory because of the difficulties inherent in accept-

ing any theory of fissure filling. "The position, size, and number of asbestos veins in rich ground make it inconceivable that the spaces they now occupy were once open fissures, and especially that many of them were open at the same time. Open fissures up to 2 inches in width, running in all directions from vertical to horizontal, extending 100 feet or more in length, and occupying in places as much as 10 per cent. of the entire rock, would be a mechanical impossibility."[4] He therefore concluded that the veins must have been formed by the action of solutions working outward from a tight crack, which is now the central fissure of the vein (Fig. 6–*A*).

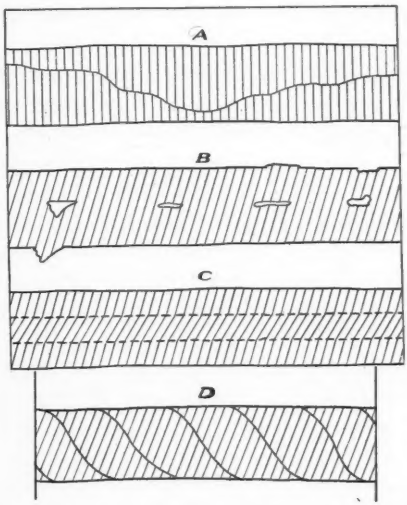

FIG. 6. Types of veins. *A*, type I, composed of two slabs of fiber, one attached to each wall, fiber meeting in center without cohering. *B*, type II, found only in "closed veins." Fiber unbroken between walls. *C*, vein like *B*, with bend in fiber, indicating change in direction of wall movement during growth. There is no break in the fiber at the bends. *D*, successive lenses of asbestos separated by threads of picrolite; formed in small faults with picrolite walls. Later, the picrolite fibers are separated and pushed into their present positions by the growth of asbestos. All stages of this procedure have been observed.

[4] Dresser, J. A.: Geol. Surv. Canada, Memoir 22, p. 65, 1913.

Although I am in entire agreement with Dresser as to the impossibility of the veins having been open fissures, there is evidence that the alternative to which he turned is not correct. For example, (1) perhaps 75 per cent. of all veins entirely lack a central fissure, and are of the type shown in Fig. 6–*B*. If replacement took place, therefore, action must have been confined to one side only of the original fissure. No reason has ever been advanced for such a peculiarity of behavior; and there is field evidence, presented later, to prove that it did not take place. (2) Replacement characteristically forms veins with extremely irregular edges, due to the fact that some parts of the rock are more easily and rapidly replaced than others. The notable straightness and regularity of the edges of asbestos veins has been repeatedly pointed out. (3) As already shown, asbestos veins occupy fissures caused by faulting. Although the majority have formed in tension cracks, many are found in the fault fissures themselves. Veins of the latter type, which nearly always have the central fissure (Fig. 6–*A*), have also the peculiarity, never to my knowledge previously mentioned in the literature, that *the fiber grows directly on slickensided surfaces.* In the three big mines at Thetford, I estimate that at least 30 to 40 per cent. of veins more than an inch wide display this peculiarity. The slickensided surfaces were not formed after the asbestos was deposited, because the fiber is not disturbed, and little tension cracks filled with fiber cut through the slickensided wall, as in Fig 5–*A*. It seems obvious, therefore, that the slickensided surfaces are the walls of the original fissure, polished by movement; and as the asbestos has formed in this fissure without destruction of these walls, *neither replacement nor solution of the original walls can have taken place.*

Perhaps a persistent advocate of replacement may maintain that replacement starting from a central fissure merely stopped at slickensided surfaces, which are notoriously resistant to replacement. Such a contention would imply that, before each such vein formed, two parallel faults, spaced about an inch apart, caused sufficient movement to slickenside the rock. A third

irregular crack, which later became the central fissure, must also have formed through the middle of this inch-thick slice; and these three cracks nowhere intersected one another. Solutions must then have entered the middle crack, but not the outside cracks, and caused replacement. I cannot believe that any such unlikely sequence of events can be invoked to account for the thousands of existing veins of this type.

Fissure-filling Hypothesis.—The theory of fissure filling assumes that asbestos crystallized from solutions filling vein cavities in the usual manner. The vein fluids are supposed to have carried the constituents of serpentine, or to have derived them from solution of the walls. The proponents of this theory have not as a rule attempted to explain away the difficulties inherent in it, but base their conclusions mainly (*a*) on various facts indicating that the replacement theory is untenable, and (*b*) on the opinion that Taber's theory is untenable, because matching structures, such as corresponding corners of the two walls of a vein, or corresponding points on a stony inclusion and the wall from which it came, are not always at opposite ends of the same fiber or group of fibers. Such things, they contend, indicate that the pressure of the growing fibers did not push the walls apart; and they turn therefore to the hypothesis of fissure filling as the only available alternative.

At Thetford, I admit, a very few cases have been seen in which matching structures are not at opposite ends of the same group of fibers. Such instances are rare, however; and in view of the apparently insurmountable objections to the hypothesis of fissure filling, I prefer to believe that they must have some explanation not yet found, rather than to conclude that fissure filling is thereby indicated. The main objections to the fissure-filling hypothesis are as follows:

1. The structural objection advanced by J. A. Dresser and mentioned in preceding pages.

2. Asbestos veins are all narrow; 99 per cent. or more of the total number of veins are less than half an inch wide, and the

largest seen by the writer was less than 3 inches wide. Fissure filling by ordinary injection of vein-forming fluids should give a much greater range of widths.

3. The fissure-filling hypothesis fails utterly to explain the outstanding fact that two entirely different types of veins occur in juxtaposition throughout the deposits. The first type has two irregular plates of fiber, attached to and apparently growing from the two walls (Fig. 6–*A*). It is always in a fault fissure where this type of vein is found. In places the two plates of fiber are separated at the center by fragments of country rock or by magnetite, in other places the ends of the fibers of the two plates come tightly together, without cohering. In the second type of vein, the fiber runs from wall to wall without break, except where broken by occasional inclusions of country rock (Fig. 6–*B*). This type forms what may be termed closed veins, lenses of fiber having no apparent connection with any other fissure (Figs. 2, 3). These two types occur everywhere throughout the deposits in close juxtaposition. If the fissures were filled with fluid from which asbestos crystallized, deposition must have begun on the walls, and the growing fibers must have met in the center to form veins of type 1, and those only. The occurrence in great numbers of veins of type 2 proves conclusively that fissure filling was not the process by which they were formed.

The proponents of the fissure-filling hypothesis have attempted to gloss over this difficulty by assuming that the fibers of type 2 veins grew from one wall only. Why the fibers should have done so, when in adjoining veins, under otherwise identical conditions, they grow from both walls, they do not attempt to explain. Their assumption, however, can be checked by field observations, and was so checked by us in the case of some hundreds of veins. Of the numerous inclusions in such veins, many have distinctive shapes which can be matched with the walls (Fig. 6–*B*), so that it can be known from which wall they have been torn away. From a study of these it was evident that approximately as many are torn from one wall as from the other. If the fiber had grown from one wall only, all inclusions would be torn from that wall.

Furthermore, the veins display certain growth peculiarities at junctions (Figs. 9–*A*, 9–*D*), which cannot be explained except by concluding that the growth took place from both walls.

Taber's Hypothesis.—As field evidence thus eliminates the possibilities of vein formation by either fissure filling or replacement, the hypothesis advanced some 20 years ago by Dr. Stephen Taber [5] must now be considered. Briefly, it supposes that the vein-forming fluids or vapors penetrated through pores and other microscopic openings of the rock and carried serpentine into tight fissures, where it crystallized as asbestos. The pressure of the growing fibers is supposed to have pushed aside the rock walls to the width of the existing veins. Dr. Taber advanced much evidence in favor of the hypothesis in his papers, but doubt of the adequacy of the force of growing crystals to accomplish the required results made geologists chary of accepting his conclusions. The definite field evidence eliminating the alternative hypotheses, however, together with the additional facts in favor of Taber's hypothesis about to be set forth, greatly strengthen the case for it.

One of the most puzzling and at the same time most illuminating features of the asbestos deposits is the closed vein. Closed veins, as already mentioned, are lenses of asbestos varying in size from the minute ones shown in Fig. 2 to the larger ones shown in Fig. 3, some of which may be 10 feet or more in length. They are termed closed, because they appear to have no connection with any cross fissure, and only rarely can the fissure they occupy be seen to extend into the rock beyond the end of the part occupied by asbestos. It is thought that before asbestos was introduced these fissures probably resembled the conchoidal cracks commonly seen within a block of glass not properly annealed. It may be argued, perhaps, in the case of the larger of these veins, that they are not really closed, *i.e.*, that connections with cross fissures might be seen if all three dimensions were visible. It is difficult to maintain this position, however, with regard to the little veinlets in bastite shown in Fig. 2. It is also difficult to suppose that

[5] Trans. Amer. Inst. Min. Eng., vol. 57, pp. 62–87, 1917, and other papers.

the many little closed veins, an inch or two in length, must necessarily intersect other unseen fissures. If, however, it is admitted that small closed veins may be formed, it follows that the same vein-forming processes may also have produced veins of larger size.

Because asbestos could and did form in closed fissures, there is no escape from the conclusion that the formative agent must have been introduced through microscopic spaces, such as the pores in the rock. The formative agent, therefore, must have been a gas or a very mobile liquid. Evidence obtained from chemical analyses suggests that the agent was probably water.[6]

If, however, the formative agent was introduced through the pores of the rock, the question arises as to why the body of the rock is not greatly serpentinized, whereas the walls of the asbestos vein are completely serpentinized. As the only original difference between the rock now thoroughly serpentinized and the remainder was the existence of a fissure through one part and not through another, it is necessary to conclude that the fissure itself was the factor causing the difference. Reaction, apparently, did not go on except where the formative agent could escape into a fissure, carrying with it the components of asbestos.

The study of closed veins and their peculiarities thus leads to several important inferences, viz. (1) The asbestos-forming agent entered through pores and other minute openings in the rock. (2) The existence of fissures was the factor determining the extent to which the agent altered the rock. (3) Most fissures were so tight that they could be bridged by the first-formed needles of asbestos. (4) After formation of the first asbestos, additions to the fiber were made at both ends, as material was supplied through the pores, so that growth took place from both walls. The central part of each vein is therefore the oldest, and the edges next the walls the youngest.

The width of the serpentine zones that flank the veins has long been known to maintain a more or less definite ratio to the width

[6] Cooke, H. C.: The Composition of Asbestos and Other Fibers of Thetford District, Quebec. Trans. Roy. Soc. Can. (3), vol. 29, sec. IV, pp. 7–19, 1935.

of the veins themselves.[7] Also, the change from peridotite to serpentine involves expansion, the amount of which depends on the reaction taking place, with a minimum of about 25 per cent. Yet certain field facts suggest that *no expansion took place when the vein walls were serpentinized.* All altered zones flanking veins display the characters shown in Fig. 7–*A, i.e.*, they are filled with little cross fissures, spaced perhaps an inch apart, and these fissures are widest next the vein and end in a point where the altered zone is in contact with the ordinary peridotite. These open joints commonly have widths, at the large end, of about one fortieth of an inch, and have been observed to attain double that width. They have no relation to any general deformation, as Fig. 7–*B*, a sketch made at one of the Black Lake pits, indicates. When the fiber is slabbed away to expose a face on the altered zone, these cracks are seen to form a pattern exactly like the shrinkage cracks in dried mud. In one cross section where the cracks were relatively large and few, I measured the actual area occupied by them to estimate the approximate shrinkage, and found it amounted to 0.8 per cent. of the area of the altered zone.

If these cracks were produced by any cause other than serpentinization, such as cooling, there is no reason for their ending as they do at the borders of the serpentine zones. If serpentinization caused actual increase in volume, the great pressures thereby set up would have rendered it impossible for such cracks to form. The conclusion seems inescapable, therefore, that serpentinization, instead of being accompanied by expansion, actually caused a slight contraction. To accomplish this, sufficient material must have been withdrawn from the altered zone, during the process of change, to keep its volume approximately constant. The shape of the joints themselves affords confirmation of this conclusion, for they are widest close to the vein, where alteration with accompanying removal of material has been most thorough, and disappear at the outer boundary of the serpentine zone, where alteration is least.

If these observations have been correctly interpreted, it seems

[7] Dresser, J. A.: *Op. cit.*, p. 60.

reasonable to infer, further, that the asbestos now occupying the fissures is composed, in part or altogether, of the materials withdrawn from the altered zones. Such a conclusion at last affords an adequate reason for the constancy of width ratio between veins and altered zones.

CONCLUSIONS.

The conception of origin thus indicated by the field facts may now be summarized. The partly altered peridotite was intensively faulted by thrust movements, and the blocks of rock between the faults were placed under strain by the drag of one fault face upon another. As the rock was both brittle and incompetent to resist stress, a great number of tension cracks were formed, many of which were only a few feet long, and many others only a few inches, or even a fraction of an inch. More than anything else they must have resembled the conchoidal fissures that may be seen in the middle of a block of glass not properly annealed; and like them are supposed to have had the walls tightly pressed together.

After faulting was completed, heated solutions or, more probably, vapors were introduced through the fault fissures and filled the pores of the rock; and wherever they found a crack or an incipient crack, with its opportunity for expansion, they began to convert the wall rock into serpentine and to carry the excess volume into the fissure. The force exerted by the growing fibers would tend to push the walls apart, and although presumably it would be incapable of doing this under normal conditions, the state of tension existing at the time might assist. Whatever the combined causes, however, the walls did move apart, and flat disc-shaped plates of asbestos were formed.

The hypothesis, it will be noted, affords an adequate explanation of both main types of veins. The closed veins are supposed to have formed in tight fissures, which the first-formed short needles of asbestos could bridge. Hence further accessions of material could be supplied at both ends, accounting for the observed phenomena, namely, fibers that cross the vein without break, and growth from both walls simultaneously. Where

faulting had broken the rock, on the other hand, and the resulting fissure may be supposed to have remained a little open, the first-formed fibers would not bridge the gap, and consequently two plates of fiber, one growing from each wall, would be formed. Any fault, however, has places where the walls touch, and if the theory is correct, there should be places in veins of the second type where the fibers run unbroken from wall to wall. This is actually the case.

Difficult as it is to conceive of relatively weak asbestos fibers having power to push fissure walls apart, the theory is supported by a great variety of further evidence, facts very difficult of explanation otherwise. Thus, where a vein occurs on one side of a fault fissure, with much picrolite on one side and little or none on the other, there is commonly a very skimpy development of asbestos on the picrolite side, and a more normal development on the other (Fig. 8). The theory presented affords a reason,

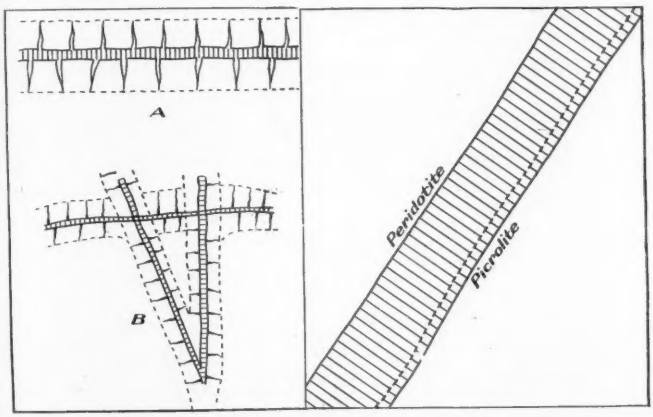

FIG. 7. (left). *A*, contraction fissures in serpentine zones flanking asbestos vein. Width of fissures is exaggerated. *B*, sketch of vein arrangement, Black Lake pit, showing contraction fissures are related to individual veins, and are not a result of general stress.

FIG. 8 (right). Asbestos vein lying between serpentinized peridotite and picrolite, along the edge of a fault. The thickness of the asbestos plate on the picrolite side is much less than on the other side.

because the picrolite side of the vein wall was already serpentine before the vein was formed, hence subsequent action by solutions or vapors could not cause much chemical or physical change.

The fiber of many veins is not straight, but bent as shown in Fig. 6–*C*. In many cases there are several such bends. These bends are not the result of deformation; deformed fiber occurs but rarely, and when seen is easily distinguished by its crushed appearance. It is difficult to explain veins of this type except by the hypothesis herein advanced, but by it the bends are readily explained as due to changes in the direction of movement of the walls, as vein growth pushed them apart.

Although textbooks commonly teach that the fiber of asbestos veins lies at right angles to the walls, the statement is true only for about half, or less than half, of the Thetford veins. In the remainder the fiber impinges on the wall at angles of less than 90°, and in many the angle between fiber and wall is as little as 45°. My observations indicate that in veins lying in nearly horizontal or nearly vertical positions the fiber is at right angles to the walls, but in most others it is not. In the latter, the fiber always occupies a position intermediate between the line normal to the walls and the vertical. This peculiarity is easily explained by the hypothesis that the veins, during growth, pushed the walls apart. A force tending to separate the walls of a fissure dipping, say, at 45° would oppose two forces, gravity, acting vertically downward, and the resistance of the rock to compression, acting in a horizontal plane. Of these, the force of gravity was undoubtedly the smaller; and consequently, movement of the walls would not be at right angles to the plane of the vein, but in some direction closer to the vertical. No other hypothesis has attempted to explain this peculiarity of fiber arrangement.

Veins having a central break (Fig. 6–*A*) exhibit extreme irregularity as to the position of the break; in many cases the irregularity is far more pronounced than shown in the figure. In addition, they never have any vugs. It is difficult to explain this combination of extreme irregularity with absence of vugs by any ordinary process of vein filling. Under the hypothesis

herein advanced, however, no matter how irregular the growth, the fibers must always meet tightly in the center, for if pressure at any point was momentarily relieved, growth there would go on more rapidly until pressures at all points became equalized.

Still another peculiarity of the asbestos veins is shown in Fig. 9. Asbestos veins truly cut one another so rarely that it may

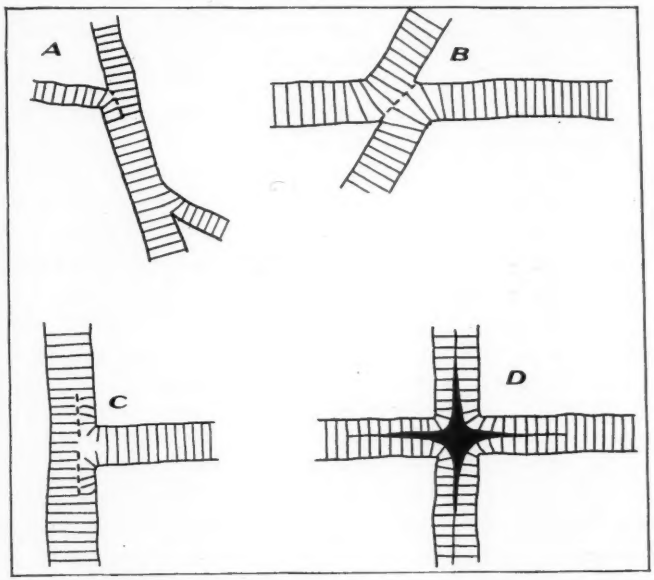

FIG. 9. Various types of vein junctions.

almost be said they never do so. During several seasons' study the writer has not seen more than one or two places where the fibers of one vein cross another. Instead, relations like those in Fig. 9 prevail. A vein entering another at a small angle has the fibers growing smoothly over the obtuse angle. The division between the fibers of the branch and those of the main vein may continue for a distance, as shown in Fig. 9–*A*, or may cease at once. A vein entering another at a right angle, Fig. 9–*C*, shows

a rather sparse growth of fibers extending around both corners, and the division ending almost at once. Two veins crossing at a small angle have their fibers arranged as in Fig. 9–*B*; and if the angle at which they cross is a right angle, the arrangement shown in Fig. 9–*D* is a common one. Junctions of veins, particularly where the angle approaches a right angle, have to be carefully examined with a glass to determine the relations, because they are favorite spots for the accumulation of magnetite and chips of wall-rock, and in the latter there is generally developed much short fiber with no particular orientation. The projecting ends of this short, tangled fiber are thus apt to give junctions a fuzziness not readily penetrated by the unaided eye. The black cross at the center of the junction, Fig. 9–*D*, depicts magnetite, which in this instance largely replaced the serpentine and short fiber. These pecularities are readily explicable by the hypothesis that the serpentine grew outward from both walls, but are difficult of explanation by any other hypothesis.

Still other pecularities occur, to explain which it seems necessary to go further into the probable mode of operation of the serpentinizing agent, which, as mentioned, appears to have been water only. One such peculiarity is the occasional occurrence of asbestos veins where the surrounding rock is not the ordinary partly serpentinized peridotite. In the collection of Dr. Eugene Poitevin, mineralogist to the Geological Survey of Canada, there is a fine specimen of an asbestos vein running through massive chromite. The vein is of the closed type, with fibers running unbroken from wall to wall. Again, in many instances veins are found within masses of pure serpentine, and notably in fault zones where both walls consist of picrolite formed during faulting. Neither chromite, serpentine, nor picrolite can be supposed to have contributed toward asbestos formation; the chromite, because it has not the necessary constituents; the serpentine or picrolite, because they could only do so by solution and recrystallization which, the field facts show, did not take place. Again, some veins (Fig. 6–*D*) are composed of succeessive lenses of fiber separated by thin plates of picrolite which appear in cross section as strings. The strings cross the strike with smoothly

curving courses at an average angle of 35° to 45°, and the fibers of the enclosed lenses may vary in position from nearly normal to the strike to nearly normal to the picrolite fibers.

To account for these and other peculiarities, the suggestion is advanced that the asbestos-forming agent, supposedly water, arriving through pores and other microscopic rock openings, entered the various minute fissures laden with the constituents of asbestos. Crystallization of the dissolved material would leave the water in the fissure less saturated than the water in the walls, and an interchange would tend to begin, with dissolved materials passing to the edge of the fissure where deposition was proceeding, and water returning into the rock where it could again attack the olivine and pyroxene to form more serpentine. Interaction between a particle of olivine and one of water, tending to cause expansion, would set up momentarily a high local pressure at that point, and this might assist in the transfer of material, as substances tend to go into solution at a point of stress, and to crystallize as soon as they reach a point where stress is relieved. Whatever the chemistry of the reaction, however, the facts seem to point to the initial minute fissure being filled with a solution of the constituents of serpentine; and if so, the solution would naturally run along and fill the crack, even though it should run into chromite, serpentine, picrolite, or any other available material. This being the case, there seems no reason for believing that deposition would not take place from such a solution at any place along the crack; and if the process of molecular interchange was sufficiently active, a vein of fair size could develop. It seems absolutely necessary to assume some such process for veins like those in Fig. 6–*D*. The threads of picrolite shown in the figure could have supplied no great amount of material to the vein, even if they showed signs of attack by solutions, which they do not. Their sole function, therefore, must have been that of a floor to which asbestos fibers could anchor and along which solutions could run.

The ribbon veins likewise are very difficult of explanation except by the hypothesis outlined. These veins comprise a large number of individual asbestos veinlets, with the fiber un-

broken from wall to wall, the veinlets separated by equally thin slabs of serpentine. Both veinlets and slabs are inclined at a small angle to the walls of the ribbon, and no relation exists between the thickness of a vein and the thickness of the serpentine slabs on either side. Unless the serpentine slabs are considered as similar to the picrolite strings mentioned in the last paragraph, in that their function was merely to act as an anchorage to the asbestos and a floor along which solutions might creep, the explanation of the ribbon veins becomes most difficult.

Still further evidence in support of this contention is afforded by veins of the type shown in Fig. 8, in which the growth of fiber is much sparser on one side than on the other. The picrolite on which the fiber grows sparsely can have supplied none of the materials necessary for asbestos growth, consequently those materials must have come either through the picrolite from the rock beyond, or from the other side of the fissure, through the already formed plate of asbestos. In either case it is evident that the necessary materials must have been supplied much more slowly than to the other wall of the fissure, and growth in consequence was much less.

SUMMARY.

In this paper the geological setting of the asbestos deposits is outlined, and the relation of the veins to faults is described.

New field evidence is presented, proving (*a*) that any theory of origin involving solution or replacement of vein walls is untenable; (*b*) that vein formation by ordinary processes of fissure filling was impossible.

Taber's theory that the fiber commenced to crystallize in tight fissures, the walls of which were pushed apart by growth of the fiber, aided probably by tensions set up by deformative movements, affords an adequate explanation of all known phenomena, with one possible exception (p. 365). The theory has been further developed and extended to afford an explanation of various features not previously described.

Geological Survey of Canada,
Ottawa, Canada,
Feb. 27, 1936.

ORE DEPOSITION SOUTH OF OURAY, COLORADO.

PART I.

ROBERT S. MOEHLMAN.

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(*To be concluded in next number*)

ABSTRACT.

In the western part of the rugged San Juan mountains of Colorado is a mining district which has produced over 250 million dollars, principally in gold and silver. This paper is concerned with an area in part of that district including many of the principal producers. The mountains in the region are formed of a dissected pile of Miocene volcanic rocks over 4000 feet thick, resting on older sedimentary formations. The structure of the region is dominated by a down-faulted block eight miles in diameter, located in the area where the Silverton volcanic series reaches its maximum thickness. Outward from this block are radial fractures occupied by quartz veins; along the western margin of the block are chimney ore deposits. There are two types of rock alteration: the intense altera-

tion to quartz and sericite immediately adjacent to the veins, and the regional alteration, consisting of calcite, chlorite, and sericite.

The ore deposits vary according to their environment. The factors affecting vein widths and values may be summarized: (*a*) In many cases, veins follow fissures previously occupied by dikes. (*b*) Wall rock control is apparently the result of chemical as well as of physical differences in the wall rock. (*c*) A pre-ore fault transverse to a vein may cause a change in character of the vein at the intersection. (*d*) A pre-ore fault along a vein fissure may cause certain directions of the fissure to be favored for ore deposition. (*e*) Veins show marked vertical changes in the depths attained by mining, due to hypogene zoning. (*f*) Zoning has also caused areal variation in the ores; enargite occurs in the chimney ore deposits but not in the outlying veins. In the veins, sulphides are less plentiful farther west, away from the down-faulted block. (*g*) Secondary enrichment has been of no practical importance for the veins.

The microscopic examination of ore and gangue minerals clearly demonstrates that replacement has been important in the formation of the ore deposits. In the veins, the earliest stage of mineralization recorded is the formation of barren gangues, including barite, carbonate, and other minerals. Toward the end of the formation of the early gangue minerals, the early metallic minerals were deposited, including hematite, pyrite, arsenopyrite, and sphalerite. Then, the bulk of the quartz was deposited, closely succeeded by formation of tetrahedrite, chalcopyrite, galena, and gold. Mineralization closed with deposition of barren gangue. The important factor in determining whether a vein should be productive or not was the permeability at the time of deposition of the later sulphides.

The chimney ore deposits exhibit a more complex sequence than the veins. Enargite, which is confined to the chimneys, was deposited during much of the period of mineralization.

The ore deposits of the district are classified as leptothermal, a division proposed by Graton for deposits which bridge the gap between the epithermal and mesothermal zones.

INTRODUCTION.

THE author spent the summer of 1934 preparing detailed geologic maps for a mining company near Ouray and devoted the subsequent winter to a laboratory investigation of thin and polished sections; the results of this work were embodied in a thesis submitted in partial fulfillment of the requirements for a Ph.D.

degree at Harvard University. During the summer of 1935, field service as assistant to W. S. Burbank of the U. S. Geological Survey gave the opportunity to check further some of the conclusions in the thesis.

It is a pleasure to acknowledge the courtesy and co-operation of some of the individuals who made this paper possible. Mr. Burbank offered helpful advice regarding field relations. Messrs. Frank Eichelberger and H. B. Van Sinderen have granted permission to use data gathered while in their employ. Field work was facilitated by the co-operation of Richard Anderson, Frank Mahoney, J. T. Shimmin, and Charles Tonry. At Harvard University, the advice and criticism of Professors E. S. Larsen, D. H. McLaughlin, and K. F. Mather were of value. Especially helpful in laboratory work and in the preparation of the manuscript was the searching criticism of Professor L. C. Graton. Any merit in the photomicrographs is due to the expert work of Mr. E. B. Dane, Jr.

GEOGRAPHY AND HISTORY.[1]

The ore deposits considered in this paper lie in the western part of the San Juan Mountains, a lofty mountain group near the southwestern corner of Colorado (Fig. 1). The three mining towns of Ouray, Telluride, and Silverton form a right triangle, with Ouray-Telluride as the short leg of ten miles. The portion of the western San Juan mining district considered in this paper includes many important producers such as the Camp Bird, Tomboy, Smuggler-Union, Revenue (Virginius), Yankee Girl, and Barstow. The Shenandoah-Dives and Sunnyside mines are to the south and east of the area described.

The first prospectors to penetrate the western San Juan region reached Silverton in 1860, but the "rush" to the region began only after a treaty was made with the Indians in 1873. Most of

[1] Historical data from Ransome, F. L.: U. S. Geol. Surv., Bull. 182, pp. 19–24, 1901.

the important lodes were located in the next decade. The chimney ores of the Red Mountain district were not recognized as early as the lode deposits, but once discovered in 1881, a great

FIG. 1. Southwestern Colorado, showing limits of San Juan Mts. (after Atwood & Mather).

boom resulted which lasted until 1896, when it came to an abrupt end because of the fall in price of silver along with exhaustion of some of the ore bodies.

PRODUCTION.

The district as a whole has now passed its hey-day of activity. Large-scale operations ceased at the Camp Bird in 1916, at the Revenue Tunnel about 1919, at the Liberty Bell in 1921, at the Tomboy in 1926, and at the Smuggler-Union in 1928.[2] Since then, leasing operations have yielded ore from various lodes; in December, 1935, the Smuggler was milling 200 tons daily and Camp Bird 80 tons.

[2] Dates obtained from Mr. Charles Tonry of Telluride.

The veins in the area covered by Fig. 2 have produced over $100,000,000 in gold and silver. The average grade of ore mined varied from $6.80 at the Liberty Bell to about $28 per ton at the Camp Bird. Of course, much higher values were en-

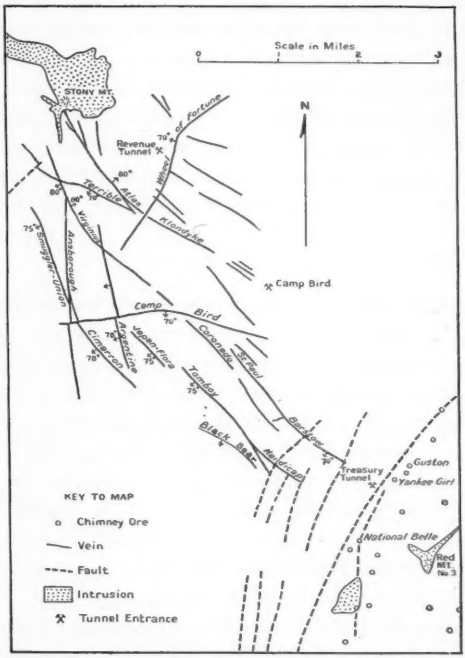

FIG. 2. Principal veins and chimney deposits (Modified from Burbank and Ransome). See Fig. 1 for location.

countered locally, but on the whole the veins were profitable not because of high-grade ore but because of regularity, which led to economical operation. Some mines derived practically all their returns from gold; for example, the Camp Bird, which produced over $27,000,000, and the Tomboy, which worked the Tomboy, Japan, and Argentine veins to produce $23,000,000. Other veins had approximately equal content of gold and silver, including the

Liberty Bell (over $16,000,000) and the Smuggler-Union (over $20,000,000).[3] Still other veins were lead-silver veins with very little gold; to this class belongs the Virginius (about $12,000,000[4]).

Production from the chimney deposits was much less important than that from the lodes, but the former was a "poor man's district" with much "shipping ore." The Yankee Girl mine produced 3,000 tons of ore averaging $150 per ton; some pockets from the Guston mine ran $14,800 per ton.[5] The value of the ore was primarily in silver, with gold very subordinate. The base-metal content per ton was high; in most cases the ore ran well over 10 per cent. of copper or lead.

GENERAL GEOLOGY.

The western San Juan mining district is an example of mineralization at widely separated times in nearly the same place. The earlier mineralization, dated by Burbank[6] as late Cretaceous or early Eocene, is represented by blanket ore deposits and fissure veins in Paleozoic and Mesozoic sedimentary rocks in the vicinity of Ouray. Associated with and just preceding this mineralization were intrusions of quartz-monzonite porphyry, occurring as dikes, sills, and laccoliths near Ouray. The major producing mines from these earlier deposits are all located north of the town.

This paper is concerned with the deposits of later age which occur in Tertiary volcanic rocks south of Ouray. The basal Tertiary formation, the Telluride conglomerate, contains some pebbles and low-grade placer gold from the older veins. Above this conglomerate are layers of volcanic rocks, having an aggregate thickness of over 4,000 feet. In the western San Juan mountains, there are three principal divisions of volcanic rocks, separated by intervals of erosion: the San Juan tuff at the base, the Silverton series, and the Potosi series. All these are considered to be of Miocene age.[7]

[3] Cf. C. W. Henderson: U. S. Geol. Surv. Prof. Paper 138, 1926.
[4] Figure supplied by Anna Morse, president of Reynolds-Morse Co.
[5] Ransome, F. L.: *Op. cit.*, p. 112.
[6] Burbank, W. S.: Colo. Sci. Soc. Proc., vol. 12, no. 6, p. 210, 1930.
[7] Cross, W., and Larsen, E. S.: U. S. Geol. Surv. Bull. 843, pp. 50–53, 1935.

Volcanism of Silverton time showed a marked areal concentration; in the Silverton quadrangle the rocks of this age attain a thickness of over 3,000 feet, filling an erosion basin. Outward from this basin, the thickness of the series diminishes rapidly; northwest of Telluride it pinches out completely, so that the Potosi series rests directly on the San Juan tuff. The subdivisions of the Silverton series in order of age are:[8] the Picayune andesite, Eureka rhyolite, Burns breccia and Burns latite flow, the pyroxene andesite, and the Henson tuff. Of these, the Picayune andesite appears to have the widest distribution, making up the part of the Silverton series which extends westward to Camp Bird and Sneffels.[9]

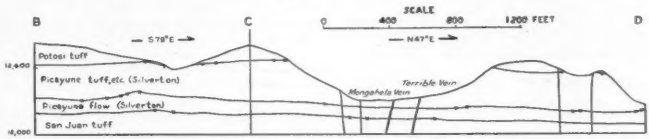

FIG. 3. Volcanic rocks near Stony Mt. Crosses indicate surveyed points within 400 ft. of section line.

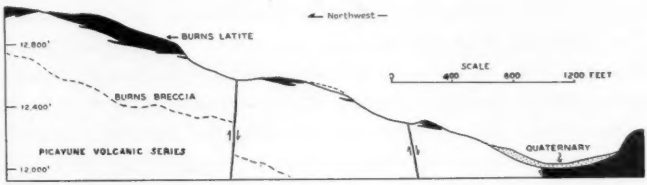

FIG. 4. Silverton series west of Red Mountain, showing lava flow intrusive into its base.

In the western part of the area considered, the various volcanic layers have a regular "layercake" arrangement (Fig. 3). In the vicinity of Red Mountain, however, contacts between the various layers are highly irregular (Fig. 4). The Burns quartz latite

[8] Cross, W., et al.: U. S. Geol. Surv., Geol. Atlas 153, p. 9, 1907.

[9] Burbank, W. S.: Written communication, 1935.

flow is intrusive into its base here, sending dikes and sills into the underlying Burns breccia in complex fashion. Some of these apophyses are banded and have produced parallel banding in the adjacent intruded breccia. Evidently the Red Mountain-Silverton area was a scene of heavy volcanic outbursts alternating with vigorous erosion during Silverton time.

Some time after the extrusion of the Potosi series, intrusions and fracturing occurred, followed by the mineralization with which this paper is concerned. The younger intrusive rocks vary more than the intrusions associated with the older mineralization near Ouray. Varieties include quartz monzonite, diorite, gabbro, and granite porphyry. In the area shown in Fig. 2, two types of late Tertiary intrusive rocks are found—the gabbro-diorite stock and associated dikes near Sneffels, and the quartz-monzonite porphyries near Red Mountain. The stock and associated dikes near Sneffels are older than the mineralization, but the intrusions in the vicinity of Red Mountain were probably derived from a magma reservoir which was genetically connected with mineralization.

The regional fracture pattern has been ably described by Burbank, who points out that the dominant structural feature of the region is a down-faulted block surrounded by radial fractures The depressed block has the shape of a shield about eight miles in diameter with its point at Silverton and its northwest corner a mile north of Red Mountain. This down-faulted block is in the region where the Silverton series reaches its greatest thickness. A net displacement of 1,000 to 2,500 feet is given by Burbank.[10] Intrusions of quartz monzonite occur along much of the periphery of the block; these are later than the faulting, since they follow or cut across faults without displacement. Although the larger intrusive masses are thus later than the faulting, many dikes are clearly older. Burbank has suggested[11] that the regional fracture pattern was developed by doming, followed by subsidence of the central block as intrusions worked up toward the surface, relieving the pressure below the dome.

[10] Burbank, W. S.: Colo. Sci. Soc. Proc., vol. 13, p. 162, 1933.
[11] *Idem*, pp. 174–182.

Some of the faults at the western side of the fault block lie in the area covered by Fig. 2. These are nearly vertical in dip (Fig. 4); the eastern side has been down-dropped in nearly every case. Very noticeable along the faults parallel to the edge of the sunken block are wide zones of shattered rock, from five to fifty feet in width. Certain features strongly suggest that these zones are primarily due to tension: (1) Microscopic examination shows less than 10 per cent. of pulverized rock in the shattered zones; there was widespread shattering but very little grinding of the rock. (2) The branching, discontinuous pattern of some zones is a likely result of tensional shattering. (3) On some zones there has been little or no displacement. Thus, the shattered zones were probably formed by tension during doming: later readjustments during subsidence of the central block would be localized along these previously formed zones.

THE ORE DEPOSITS.

Ore occurs in quartz veins and chimney deposits. The quartz veins carry gold and silver in varying proportions. Veins vary in width from a few inches to over ten feet, in most cases being two or three feet; the narrow veins are remarkable for their continuity, persisting for several miles and having stopes thousands of feet long. Sulphides are minor in amount in comparison with the quartz gangue; but the gold and silver are closely associated with the sulphides. Practically all the gold is free, and the silver is derived from tetrahedrite and galena. Other sulphides present in important amounts are pyrite, sphalerite, and chalcopyrite. The principal gangue minerals associated with quartz are barite, sericite, calcite, rhodocrosite, adularia, epidote, and fluorite.

The attitude and relation of the veins is shown in Fig. 2. Except for the east-west Camp Bird vein, the general trend is northwesterly; dips are steep, most of them between 70° and 80°. Much of the vein material has been deposited as filling in open space, but replacement has been more important than most descriptions of the region indicate. The fissures give evidence of

more or less shearing; thin seams of gouge facilitate mining on many veins.

The ores found on the western slopes of Red Mountain are irregular bodies, having the general shape of flattened cigars that stand nearly vertical. The larger bodies vary from 10 to 50 feet in length, 5 to 15 feet in width and from 50 to over 900 feet vertically. Consisting of massive sulphides with relatively little gangue, the ore contrasts markedly in appearance with the lode ores. The bodies were more difficult to find and harder to follow than the veins; the grade of ore was erratic but generally much higher than in the veins.

ROCK ALTERATION.

Rock alteration may be considered under two heads: that immediately connected with the veins and chimney deposits, and the widespread alteration found in rocks regardless of the immediate presence of a vein or chimney.

The principal minerals developed in the widespread alteration of the western San Juan region are calcite, sericite, and chlorite. The amount and proportions of minerals developed by alteration depend in part upon the mineralogy and permeability of the attacked rocks. Thus, the quartz latites contain more sericite and less chlorite than the andesites. Except in the andesite dikes, which originally contained a considerable amount of femic minerals, both carbonate and sericite are present in greater amount than chlorite; in the dike rocks, carbonate and chlorite predominate over sericite. As examples of the effectiveness of permeability in alteration, the San Juan tuff and the Burns breccia may be cited. Both of these rocks are clastic, composed of many fragments; both are much more altered than the relatively impermeable flows and flow breccias.

The regional alteration shows an areal variation in intensity which corresponds generally with the zoning of the ore deposits. Immediately west of Red Mountain, rocks are altered to a greater extent than those farther west, although secondary minerals are the same. On the slopes of Red Mountain itself, regional alteration

is even more intense. Here the attacking solutions have largely overcome the effect of primary mineralogy, so that it is difficult to recognize rock types.

Adjacent to veins, the wall rock is intensely altered for a distance of one to ten feet. All types of wall rock are converted to quartz and sericite with some disseminated pyrite. Quartz makes up 50 to 80 per cent. of the altered wall rock, and sericite most of the remainder; this involves important additions of potash and silica. Calcite is present in much less quantity than in the widespread alteration, but in some cases may be present in nearly as great amount as sericite. Chlorite is unstable in this zone and is practically obliterated.

Although the wave of alteration near the veins shows a ruthless chemical attack, original textures may be preserved with surprising fidelity. For example, adjacent to the Virginius vein, a narrow dike is seen to be converted to an aggregate of quartz and sericite; there are no remains of the plagioclase, secondary carbonate, and chlorite seen in the same dike one hundred feet away from the vein. Yet the original texture of the plagioclase laths is beautifully preserved in the altered rock.

On the western slopes of Red Mountain, the cigar-like ore bodies are surrounded by zones of heavily silicified rock, with some barite and kaolin, according to Ransome.[12]

FACTORS CONTROLLING ORE DEPOSITION.

The ore deposits of the western San Juan mining district exhibit considerable variation according to structure, adjacent country rock, and areal and vertical position. The study of where and how the deposits vary is the subject of the following section of this paper.

Influence of Pre-Ore Intrusive Bodies.—Veins cut both stocks and dikes. In the stocks they are more discontinuous than in the volcanic rocks. Purington noted for the stocks south of Telluride that the veins swell and pinch more abruptly and that a reticulated structure may be prominent in veins occurring in

[12] Ransome, F. L.: *Op. cit.*, p. 104.

diorite.[13] Moreover, in the vicinity of a stock, the regional fracture pattern is disturbed. As veins approach the Stony Mountain stock, they split and feather out (Fig. 5).

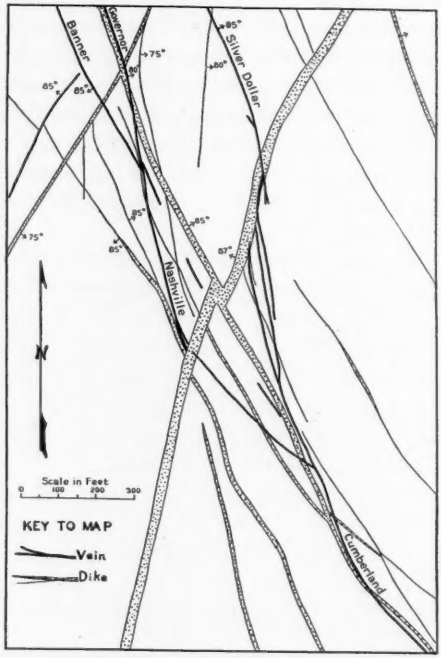

FIG. 5. Cumberland vein system, south of Stony Mt.

The intimate relation of veins and dikes in the region should be emphasized. In many cases, fractures occupied by dikes have been reopened and the new space filled with vein material. The Wheel of Fortune composite dike, which was formed by at least three injections of magma, is followed by a quartz vein along much of its length of over two miles. A narrow dike is followed by a branch of the Virginius vein for two hundred feet. Near

[13] Purington, C. W.: U. S. Geol. Surv., 18th Ann. Rept., III, p. 775, 1897.

Silverton, Burbank has described several veins following dike walls; among these, the Shenandoah-Dives vein is known to follow an andesite dike for 4800 feet horizontally and 1700 feet vertically.[14]

Where a vein fracture meets a dike at an acute angle, it tends to turn and follow the dike for some distance before crossing over to the other wall (Fig. 5). This effect on the geometry of the vein fissure suggests that the dike was present not only when vein material was deposited but when the vein fissure first formed.

Dikes have not been effective as "barriers" to mineralizing solutions since dikes and veins are more or less parallel; both dip steeply, so that their intersections are steep and offer little resistance to upward-rising solutions.

The presence of a dike on the wall of a vein may introduce a different wall-rock control, affecting ore deposition. Also, it is of practical importance that a dike on the hanging wall of a vein tends when mined to "break down" with the the vein and dilute the ore.

Wall Rock Control.—The San Juan district has often been cited as an example of control of ore deposition by wall rock. And certainly this is a district where a rhyolite, or quartz latite, cap rock has proved very unfavorable to ore deposition. Below the Potosi rhyolite flows, in the basal Potosi tuff and in the underlying rocks, veins are strong quartz lodes containing various sulphides. However, in the Potosi flows, "veins" take on an entirely different aspect. Typically, a shattered silicified zone with perhaps a few specks of pyrite indicates the path taken by the mineralizing solution; there is no vein quartz visible to the naked eye. The fractures in the zone are somewhat divergent in strike and are very difficult to distinguish from weathered joint cracks.

Spurr [15] has emphasized the effect of wall rock on ore deposition in the Camp Bird vein; here stoping was confined to the San Juan tuff except for some small stopes in the Silverton series.

[14] Burbank, W. S.: Colo. Sci. Soc. Proc., vol. 13, p. 185, 1933.

[15] Spurr, J. E.: Econ. Geol., vol. 20, pp. 115–152, 1925.

But on other veins, stoping was not so closely limited to one formation: the Smuggler vein was the same width in San Juan tuff and Silverton series and was stoped to 150 feet above the base of the Potosi tuff.[16] The Virginius vein was stoped from 200 feet above the base of the Potosi series to over 1,500 feet below the top of the San Juan tuff (Fig. 6).

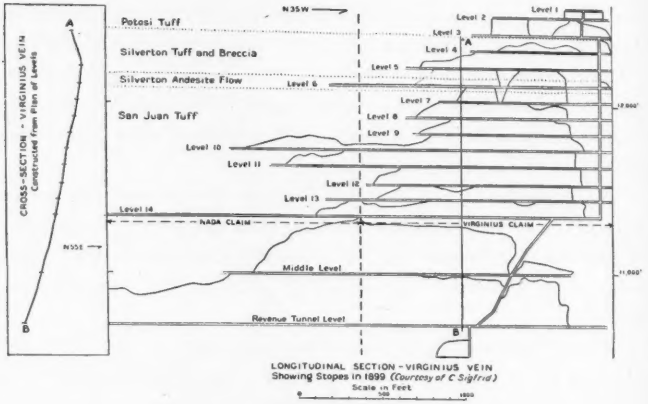

FIG. 6.

In the vicinity of the Treasury Tunnel, the character of the veins differs markedly according to the wall rock: In the underlying San Juan tuff and Picayune andesite are wide quartz veins containing much sulphide, including pyrite, sphalerite, chalcopyrite, and galena; but in the Burns breccia and the Burns flow the same veins are represented by silicified replacement zones showing much pyrite. The replacement zones in the Burns rocks are irregular and often follow branching fractures; the pyrite in these zones is in coarse cubes up to one centimeter across; other sulphides and vein quartz are scant. Also, between the Burns breccia and the Burns latite flow, a further difference is apparent:

[16] Purington, C. W.: *Op. cit.*, p. 774.

in the breccia, pyritized zones are much better developed; some fractures were observed to bend and "peter out" at the base of the massive latite flow.

The Burns breccia, apparently so unfavorable in the vicinity of the Treasury Tunnel, is productive elsewhere. South of Silverton, ore occurs in the Burns rocks, probably because of two qualifying factors: the Burns rocks are underlain here not by andesites but by the Eureka rhyolite, and andesite dikes occur along the walls of some vein fissures.[17]

From the foregoing data, it is apparent that although any of the rocks below the Potosi flows *could* carry ore, there are differences in favorability among the various formations. A fragmental rock is more favorable than a flow of equivalent composition, and andesite is more favorable than quartz latite. In some cases, the effect of differences in wall rock may be slight, but where other factors combine, a change in character of wall rock may serve as the proverbial "last straw," so that deposition occurs principally in one rock. Relative favorability of wall rock is summarized in the following list:

1. San Juan tuff—clastic andesite breccia.
2. Picayune formation—andesitic clastic breccias, flows, tuff, and flow breccia, also some quartz latite. In this formation, the clastic breccias are more favorable than the flows and flow breccias.
3. Burns breccia—clastic quartz latite breccia.
4. Burns latite—quartz latite flow.
5. Potosi tuff—quartz latite. (Possibly this is more favorable than the Burns breccia; the same vein was not observed in the two rocks.)
6. Potosi flows—quartz latite flows, more silicic than the Burns. Ore never found in these flows.

In what way is wall rock control operative? What differences in character of rocks cause differences in the veins formed in them? First, the method of yielding to stress differs. Tough, plastic rocks when deformed sufficiently to fracture, yield one fissure. Brittle rocks, on the other hand, are likely to fail along a shattered zone in which ore solutions would be dispersed. Undoubtedly, such physical changes in width and character of

[17] Burbank, W. S.: Colo. Sci. Soc. Proc., vol. 13, p. 190, 1933.

channelways affect ore deposition. Permeability may also be a controlling factor, as suggested by Spurr for the San Juan tuff. But in this connection, note that the Burns breccia, which like the San Juan tuff is a relatively permeable rock, was less favorable for ore deposition than the underlying andesite. Thus, although permeability may serve to make a fragmental rock more favorable than a flow of equivalent composition, it evidently is not the only factor when rocks of different composition are involved. Apparently, wall rock affects solutions passing through fissures in it not only indirectly through its influence on the geometry of the fissures, but directly through a chemical reaction with the solution. Rhyolite is probably a less effective precipitant than andesite because of the chemical differences between these rock types. It will be recalled that on passing into the Potosi flows, veins do not merely diminish in width; they become almost non-existent. It is true that the ryholite flows fracture differently from the underlying rocks, but this is not a case of a large vein splitting into small veinlets on passing from one rock into another. Along most "veins" in the Potosi flows there are no small veinlets. Such differences, not only in quantity but in quality of material deposited, can hardly be accounted for solely on the basis of physical character of the channelways.

It may be argued that chemical effect of wall rock should be unimportant in open space filling, because after a crust had formed on each wall, the mineralizing solutions would be insulated from the chemical effect of the wall rock. In reply to such a contention, it must be emphasized that the San Juan veins are not simple filled fissures; replacement was an important process, as will be shown later in discussion of the paragenesis of minerals.

Faults Transverse to Veins.—Post-mineral faults are of geometric importance only; no change in the character of a vein is to be expected at such a fault. However, pre-mineral faulting, to which the following discussion is confined, may have considerable bearing on subsequent mineralization.

In Fig. 2, the faults parallel to the edge of the down-faulted block are pre-ore and transverse to the strike of most of the veins.

These faults are marked by wide zones of shattered rock, probably developed originally by tensional stress before faulting occurred. In some cases, the veins cut across the shattered zones with little change in character, but in other cases, the vein is terminated at the fault. Every fissure must terminate somewhere, and a pre-existing rubble-filled cross-fault is a particularly likely place for such a termination.

The zone of faults in the vicinity of Red Mountain marks a change in character of the veins. Northwest of the cross-faults, veins are more through-going and continuous. Within the zone toward Red Mountain, fractures are more numerous but less continuous. Such a shattered region with many discontinuous fractures is less likely to be the site of a commercial vein than the region to the northwest.

Faults along the Vein Fissures.—Many of the fissures followed by veins have been the site of shearing and contain thin seams of gouge. In most cases movement along the fissure has been so slight that it is difficult to detect any displacement, but the Barstow vein follows a normal fault with a displacement of one hundred feet.

Writers have emphasized the dependence of ore shoots in many of the San Juan veins on the strike and dip of the vein. This is usually considered to be the result of pre-mineralization faulting along the vein fissures. Von Cotta long ago pointed out that in normal faulting a fissure widens where the dip is steep and pinches where the dip flattens. Purington [18] stated that the Smuggler vein was wider where the dip was steeper. Spurr [19] showed that the Camp Bird vein, which has an average east-west strike, makes ore when it trends northwesterly; this was a result of movement of the north wall of the fissure to the east with reference to the south wall. Hulin [20] noted that in the Sunnyside mine, the steeper portions of the vein were wider and richer. Burbank [21] demonstrated a relation of ore shoots to strike and dip at the Shenandoah-Dives mine.

[18] Purington, C. W.: *Op. cit.*, p. 780.
[19] Spurr, J. E.: *Op. cit.*, p. 122.
[20] Hulin, C. D.: Econ. Geol., vol. 24, p. 40, 1929.
[21] Burbank, W. S.: Colo. Sci. Soc. Proc., vol. 13, p. 188, 1933.

Vertical Zoning.—Most of the lode ore has been derived from elevations between 12,500 and 10,500 feet. The upper limit to mining is the capping of unfavorable Potosi flows. The lower limit, which varies considerably on different veins, is a gradational boundary due to gradual decrease in grade of ore together with rising costs at greater depths.

The Camp Bird vein offers a more striking example of vertical zoning than the other veins of the region. This vein is exposed for 2,300 feet vertically by mine workings. Specularite and epidote are said to make their appearance in the intermediate levels of the mine (about 11,000 feet elevation) and to increase with depth.[22] The specularite mineralization is an integral part of the gold-quartz vein, as shown by the intimate association of gold with specularite (Fig. 12); appreciable production of gold came from the specularite-bearing portions of the vein. Spurr, describing the economically unimportant lead-silver mineralization associated with the gold at Camp Bird, said there was a change from predominating galena near the surface to sphalerite and pyrite at depth.[23]

The author observed the Virginius and Terrible veins at the surface (12,600 and 12,100 feet) and at the Revenue Tunnel level (10,700 feet). In this interval, no important mineralogic change was noted in the Virginius vein although the deeper level sulphides and quartz are coarser grained. However, the Terrible vein which has been stoped downward for 500 feet, changes from a heavy sulphide vein at the surface to a relatively barren vein at the tunnel level, containing very scanty sulphides; thus, the mineralogy in this vein changed more rapidly with depth than in the Virginius vein.

The vertical changes in mineralogy of veins in the region are probably largely dependent upon relatively shallow depth of formation. What has by some been ascribed wholly or mainly to

[22] Butler, B. S., and Burbank, W. S.: Trans. Amer. Inst. Min. Eng., Mining Geology Yearbook, p. 350, 1929.

[23] Spurr, J. E.: *Op. cit.*, p. 144.

the playing out of supergene enrichment was really due to hypogene vertical zoning, according to Perry.[24]

There has been a tendency among some engineers to believe that a certain elevation (often taken as 11,300 feet, from Camp Bird's third level) can be projected throughout the district as the horizon along which ore is most likely to occur. This belief encourages long drifts with few raises or winzes; such a procedure is to be deprecated. *A priori* considerations should not lead an engineer to extended development on one level without thought of what may be above or below. Even in the famous Camp Bird vein, a rich ore shoot was found in the easternmost part below the third level.

Areal Variation Due to Zoning.—The areal variation in ores in the region is on a larger scale than the vertical variation. The Red Mountain district of chimney ores was a "hot center" of mineralization relative to the veins to the northwest. The form of these ore bodies and the abrupt vertical changes in mineralogy suggest fumarolic deposition. The intense regional alteration of all rocks in the vicinity of the chimney ores is evidence of a more intense thermal environment than prevailed to the northwest. Mineralogical evidence also points to a higher temperature of deposition in this region of chimney ores. Enargite occurs in abundance in practically all the chimney ores but is not present in the lodes to the northwest. And it may be significant that some of the pyrite in the chimney ores occurs in octahedrons. Spectographic analyses by Mr. G. A. Harcourt of the Harvard Laboratory of Mining Geology showed that in the Virginius and Terrible veins tetrahedrite is present (with practically no arsenic), while the Yankee Girl chimney has tennantite (with a minor amount of antimony); this probably indicates that antimony is of lower intensity significance than arsenic.

The veins show some variation, according to their distance from the down-faulted block on the western margin of which the Red Mountain chimney ores are situated (Fig. 2). Immediately west of Red Mountain Creek, veins are much richer in sulphides

[24] Perry, E. H.: Field Notes, Secondary Enrichment Investigation, 1915.

than farther northwest. Even a casual examination of the Handicap and Barstow veins reveals a striking increase in the amount of sulphides as compared to the veins farther northwest. For similarly situated veins near the southeast margins of the down-faulted block, Burbank [25] states:

> There is a rough zonal distribution of the different kinds of ore. . . . Ores occurring in the northwesterly fissures immediately adjacent to the Animas fault-zone contain some specularite and are characterized chiefly by the base metal sulphides. . . . Ore bodies in the same fissures a mile or two farther south contain the base metals also, but argentiferous tetrahedrite becomes an abundant constituent of the ores, and barite, rhodocrosite, and manganiferous calcite become more abundant constituents of the gangue. Gold is here the less important and silver the more important constituent of the ore.

The veins in the Sneffels-Telluride region, which are much lower in base metals than those near the faulted block, show some lateral variations. The easternmost ore shoot on the Camp Bird vein, which also was stoped to lower levels than the other shoots, contained much more specularite and epidote. Purington [26] said of the veins near Telluride, "there is an increase in gold values and a decrease in those of silver from north to south in several of the principal veins." Burbank [27] also states "The Liberty Bell vein constitutes at least one individual vein in which the base-metal content of the ore definitely increased toward the east."

The relation between values close to and at a distance from the down-faulted block can be compared in a general way through the production records of San Juan and San Miguel counties: San Juan county produced about half as much gold and silver, three times as much copper, twice as much lead, and three times as much zinc as San Miguel county. Most of the production of San Juan county is derived from veins immediately southeast of the down-faulted block, and that of San Miguel county from the outlying veins near Telluride.

[25] Burbank, W. S.: Colo. Sci. Soc. Proc., vol. 13, p. 165, 1933.

[26] Cross, W., and Purington, C. W.: U. S. Geol. Surv., Geol. Atlas 57, p. 17, 1899.

[27] Burbank, W. S.: Colo. Sci. Soc. Proc., vol. 13, p. 172, 1933.

Secondary Enrichment.—For the veins of the San Juan region, secondary enrichment has not been important. This is hardly surprising in such rugged country, where there is little chance for chemical attack on the ore before it is eroded. Bastin, after a detailed microscopic study of secondary enrichment in this region, came to the conclusion that not only the gold, tetrahedrite, and galena, but most of the silver sulpho-salts, are hypogene.[28]

For the chimney ores, Ransome [29] suggested that secondary enrichment was important, but gave some data indicative of hypogene rather than supergene changes. Apparently the rich silver ore passes into barren pyrite not only downward but laterally, for " in the richer portions of the ore bodies the pyrite was subordinate and appears to have been found chiefly in the peripheral portions of the stocks." Also, there are some significant exceptions to the usual changes with depth that are difficult to reconcile with the theory of secondary enrichment. For example: " The Congress mine appears to have had an ore body consisting chiefly of enargite with some bunches of galena, from the croppings downward." Undoubtedly some secondary enrichment has been superposed on the primary vertical concentration; such minerals as stromeyerite, argentite, covellite, and native silver are likely to be secondary. But the vertical changes involving tennantite, sphalerite, galena, enargite, pyrite, and chalcopyrite are due to hypogene processes. This suggests the interesting possibility that chimney ores as yet undiscovered because the top of the cigar-like body lies just below the surface, might be of high grade notwithstanding lack of opportunity for supergene enrichment.

Vein Intersections.—It is part of every miner's lore that where two veins come together, the ore should be twice as good. Unfortunately, this is rarely the case in the San Juan region. The northwesterly veins had no effect on the Camp Bird vein at their crossings. Nor was the crossing of the Virginius with the Terrible or Montana veins effective in changing the grade of ore.

According to Mr. Charles Tonry, mining engineer at Telluride, however, the Smuggler vein widened at its intersection with the Ansborough vein.

Feb. 3, 1936.

[28] Bastin, E. S.: U. S. Geol. Surv. Bull. 735–D, pp. 65–130, 1922.

[29] Ransome, F. L.: *Op. cit.*, p. 138.

(*To be concluded in next number.*)

MICROSTRUCTURES AND METALLIZATION OF THE GOLD–QUARTZ VEINS OF CORNUCOPIA, OREGON.

G. E. GOODSPEED.

CORNUCOPIA is a small mining district situated on the southeastern flank of the rugged Wallowa Mountains, one of the higher ranges of the Blue Mountains group of northeastern Oregon. Lindgren included a description of the district in his report on the Gold Quartz Veins of the Blue Mountains of Oregon.[1] More recently Gilluly has given an excellent summary of the general geology of the region.[2]

The oldest rocks of the area are pre-Tertiary sediments and volcanics now metamorphosed to schists, hornfels and greenstones. Following deformation this complex was invaded, probably in Cretaceous time, by granodiorite accompanied by the usual retinue of porphyries, granophyres, aplites, pegmatites and quartz veins. The granodioritic mass is by no means simple; in general it consists of an earlier gneissic facies followed by irregular stock-like and chonolithic intrusions which are more acidic and trend towards the composition of trondhjemites.

After the granodioritic invasion, stream erosion produced a mature topography with a maximum relief of perhaps 3000 feet. Then in middle Miocene time profound fracturing provided conduits for extensive flows of basaltic lavas which completely flooded the middle Miocene land surface. Probably in Pliocene time well defined block faulting produced differential uplifts of several hundreds of feet with a possible maximum of several thousand feet. According to Livingstone this block faulting has had a marked control on present day topography.[3] The Pleisto-

[1] Lindgren, W.: Gold belt of the Blue Mountains of Oregon. U. S. Geol. Surv., 22d Ann. Rept., pt. 11, pp. 561–776, 1900–1901.

[2] Gilluly, J., Reed, J. C., Park, C. F., Jr.: Some mining districts of eastern Oregon. U. S. Geol. Surv., Bull. 846A, 1933.

[3] Livingstone, D. C.: Certain topographic features of northeastern Oregon and their relation to faulting. Jour. Geol., vol. 36, pp. 694–709, 1928.

cene in the Cornucopia district was characterized by vigorous alpine glaciation which has produced the usual erosional features. Deep U-shaped valleys afford vertical cross sections of two to three thousand feet (Fig. 1).

FIG. 1. General view of Cornucopia, Oregon.

Like rocks of other regions adjacent to batholithic invasions, the metamorphic rocks of Cornucopia are characterized by many kinds of veinlets. Numerous quartz-diopside-garnet veinlets are clearly features of contact metamorphism formed as replacement veinlets by emanations from the intrusive mass.[4] Some quartz

[4] Goodspeed, G. E., and Coombs, Howard A.: Quartz-diopside-garnet veinlets. Am. Mineral., vol. 17, pp. 554–561, 1932.

veinlets of earlier generation may have similar modes of origin. It is not uncommon to find granitic dikes cutting quartz veinlets, hence it is inferred that these veinlets are associated with an earlier stage of the igneous activity. In a contact breccia at Cornucopia small quartz veinlets were formed as a direct result of recrystallization of xenoliths. These small veinlets exhibit neither microbrecciation nor replacement of the quartz by later quartz or ore minerals. Such microstructures are characteristic of the larger gold quartz veins (Fig. 9).

The principal veins of Cornucopia, beginning with the most eastern one, are: Whitman, Union Companion-Red Jacket, Last Chance, Wallingford, and Valley View. All have in general a strike of N. 40° E., and a dip of 40° W., all are irregularly lenticular in shape and some range from a gouge seam to maximum widths of about ten feet. Many of the ore shoots appear to rake to the south with a pitch length of two or three hundred feet, a stope length of a hundred feet or more and a width of three to five feet. To date the Union Companion-Red Jacket and the Last Chance have furnished most of the production for this district. Interspersed with these major veins are five or more minor veins which are not as regular in strike, dip or extent. Some of the veins, as now exposed by erosion, are entirely within the granitic rock, some cut roof pendants, and some traverse the metamorphic rocks. The Union Companion Vein is situated about a mile west of the old town of Cornucopia and outcrops at an elevation of about 6250 feet, some 1400 feet higher than the town. A new low level tunnel called the Coulter tunnel is now being driven from the town of Cornucopia with the Union Companion vein as its objective. It should intersect the plane of this vein several hundred feet below the old workings some 6000 feet west of the portal. The Union vein has been worked through an adit tunnel at an elevation of 5800 feet and an inclined shaft on the vein to a depth of 900 feet. The same adit has been extended to intersect the Last Chance vein some 3000 feet to the west. The outcrop of the vein is at an elevation of about 7500 feet and the upper workings are connected with the Union Companion

adit by a long raise. Most of the upper workings of the Last Chance vein are in the metamorphic rocks, whereas granodiorite is the prevailing wall rock in the lower workings. This vein is peculiar in that it consists, in many places, of two veins, one on the hanging wall and one on the foot wall of a thirty foot aplite dike.

Slickensides, gouge, and fractures both in the quartz veins and in the contiguous wall rocks, as well as definite petrographic evidence of microbrecciation and recementation prove that movement within the veins continued during the time of their formation. Many of the veins have been subjected to much later lateral and transverse dislocation incidental to dike injections of Miocene basalt or diabase. However, as the average width of the Miocene dikes is about 50 feet and, since the dikes appear to have filled simple fissures, the amount which they have off-set the veins is usually readily determined. Aside from this dike fissuring, the veins in general have suffered but little post mineral movement except in a few instances where displacement is considerable. The Coulter tunnel encountered a well marked normal fault about 2600 feet west of the portal and but a few hundred feet east of the expected intersection of the Whitman vein. A vein which is presumably the faulted portion of the Whitman has been intersected at a distance of nearly 4100 feet from the portal. If this is the Whitman the displacement along the fault plane in the direction of the dip would be about 800 feet.

In the genetic history of the gold quartz veins separate stages are characterized by distinctive processes although the whole process of vein formation may well have been a continuous one. For the Cornucopia veins these main divisions are suggested: (1) An initial stage with predominating seritization and carbonatization; (2) An earlier quartz-forming period with pyrite and in one of the veins pyrite and pyrrhotite; (3) The chief metallization period with later quartz and carbonate; (4) Later oxidation; confined for the most part to the upper 500 feet of the veins but having in the Last Chance vein a maximum downward extension of over 2000 feet with a very limited lateral distribution.

INITIAL STAGE.

Seritization and carbonatization are evident along many joint cracks which are especially prominent adjacent to the larger veins. It is probable that the alteration proceeded gradually outward from fracture planes, since alteration borders, a fraction of an inch to an inch or more in width, parallel the joints. The granodiorite has a pinkish color and a reduction in grain size where it is traversed by the joints. In the darker colored fine grained metamorphic rocks the alteration border is much lighter in color, commonly exhibiting a silvery appearance due to sericite. These effects are accentuated along the contacts of the larger veins and in fragments of the wall rock within the veins. Since anastamosing veinlets from a main vein traverse and even pass through the altered zones, it is evident that this alteration preceded the quartz-forming stage.

Under the microscope the alteration of the granodiorite shows a gradual replacement of the feldspars by a sericite-carbonate-quartz aggregate and it is not uncommon to find one side of a feldspar crystal completely altered and the other side quite fresh. This aggregate merges from one crystal to another so that only the merest outlines of the original feldspars are discernible. Even the original quartz is attacked and partially replaced by quartz which has either been introduced with the hydrothermal solutions or in part, at least, has been a product of the alteration reaction. This relation is analogous to that held by Knopf in that most of the quartz of the Mother Lode veins has been derived from the wall rocks.[5] Biotite changes to chlorite before merging with the sericite-carbonate material, and even then lines of opaque ferruginous alteration products trace an indistinct outline of the former boundaries of this mineral. Some magnetite is associated with partially altered biotite.

Thin sections of the metamorphic rocks (biotite schists and hornfels) show in general an uneven finely matted aggregate of sericite, chlorite, and carbonate. Biotite first alters to chlorite

[5] Knopf, Adolph: The Mother Lode system of California. U. S. Geol. Surv. Prof. Paper 157, 1929.

which in turn is replaced by sericite. Some sections show an even distribution of sericite and carbonate while others are traversed by irregular veinlets of calcite which appear to have enlarged themselves by replacement. Pyrite is especially common in the altered metamorphic rock.

Altered zones adjacent to the larger veins generally contain a coarse network of lenticular joints surrounding cores of highly altered rock (Fig. 2). The joints may contain gouge, kaolinitic and sericitic material, with varying amounts of quartz. Where oxidation has taken place, these joints are iron-stained.

EARLIER QUARTZ FORMING PERIOD.

Quartz is also found in segregations that increase substantially as the vein is approached. The vein itself may exhibit a network of lenticular joints that have a striking resemblance to the joints in the altered zones. Many of these joints in the quartz contain gouge, kaolinitic and sericitic material, which may perhaps be most easily explained as relicts from the first stages of vein formation (Fig. 2).

Fragments of various shapes are found in the veins. Some of these are very thin and elongated even attaining a length of several feet. All gradations in the silicification of fragments from incipient stages to complete blending with the vein quartz are visible. Very thin inclusions pass gradually into a fine banding which may be explained as a relict of the original fragment (Fig. 3). The evidence of these structural features as well as petrographic evidence obtained from a study of thin sections points to replacement as an important mechanism of vein emplacement.

The earlier quartz is allotriomorphic granular in texture and in general has sutured boundaries. The average grain size is 5 mm. with a minimum of 1 mm. and a maximum of 15 mm. Perhaps its most striking microscopic characteristic is its pronounced turbidity. High magnification shows that the turbidity is due for the most part to an abundance of minute vacuole-inclusions. The larger of these are about 0.05 mm. in diameter; the smaller are

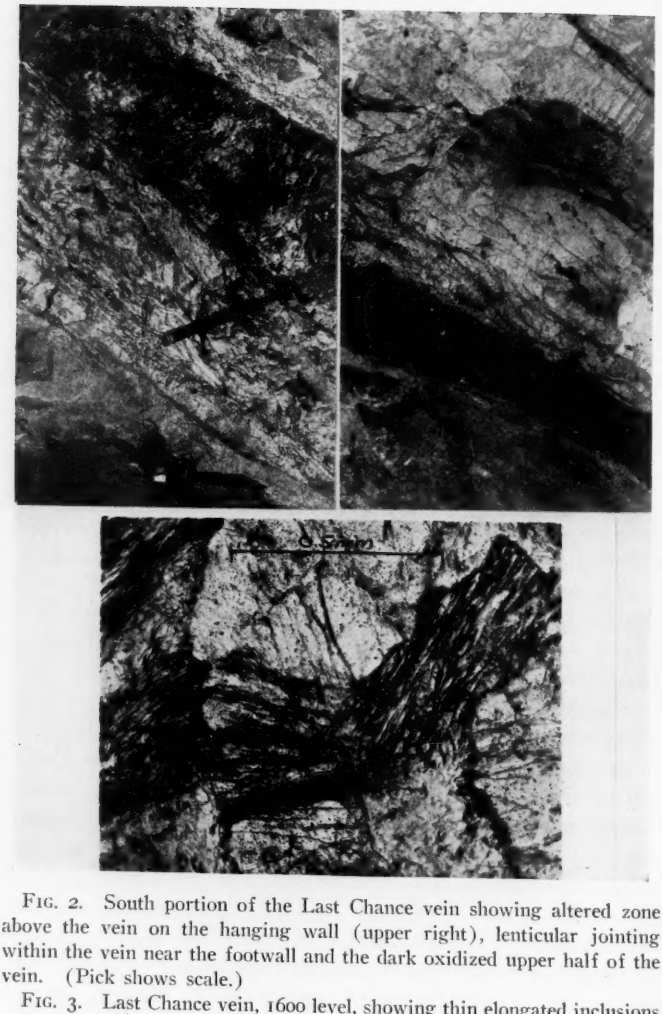

FIG. 2. South portion of the Last Chance vein showing altered zone above the vein on the hanging wall (upper right), lenticular jointing within the vein near the footwall and the dark oxidized upper half of the vein. (Pick shows scale.)

FIG. 3. Last Chance vein, 1600 level, showing thin elongated inclusions and banding near the hanging wall.

FIG. 4. Horizontal lines of vacuole-inclusions in the quartz (center) appear to be connected with the sericite on either side. Last Chance vein.

about 0.001 mm. in diameter. Some with angular boundaries may be considered negative crystals (0.01 mm.), some are amœba-like in form, others are rounded and others are tube-like. Some show alignment—others are haphazard in distribution.

Similar inclusions have been noted by Ferguson [6] and Knopf [7] in their thorough studies of the California quartz veins.

Sections of altered rock adjacent to the veins commonly show sericite replaced by quartz. In this quartz, the former position of blades and foils of sericite are indicated by lines of vacuole-inclusions (Fig. 4). In view of these relations it is possible that some of the very regular lines of vacuole-inclusions that disregard crystal boundaries may be due to an original alignment of a replaced mineral such as, for example, mica in a schistose rock. However, a common interpretation for vacuole-inclusions having a marked linear alignment traversing many quartz grains is that they have been formed subsequently to the quartz.[8] In some cases the irregular grouping of vacuole-inclusions suggests relicts of replaced angular fragments of an originally fine grained rock such as a hornfels. It may be readily observed, especially in thicker sections, that some of the lines of vacuole-inclusions within individual quartz grains are in reality distributed along crystal planes which presumably marked a momentary cessation in the process of crystal growth.

In some sections showing silicification of an altered rock, the vacuole-inclusions are arranged in a position roughly transverse to the initial veinlet and yet independent of the quartz anhedra. It is possible that this arrangement may have been caused by a previous transverse or comb-like structure of the earliest quartz and that the vacuole-inclusions were driven to the crystal faces of this quartz by crystallization pressure. The process might be somewhat analagous to the ability of growing porphyroblasts to free themselves from inclusions.[9] Some vacuole-inclusions are

[6] Ferguson, J. G., and Gannett, R. W.: Gold quartz veins of the Alleghany district of California. U. S. Geol. Surv. Prof. Paper 172, 1932.

[7] *Op. cit.*

[8] Johannsen, Albert: Petrography. Vol. II, Univ. of Chicago Press. 1932.

[9] Harker, A.: Metamorphism. Methuen & Company, London, 1932.

not affected by the immediately following crystallization. This may be due to the lack of any differential pressure, or it may be due to the alignment of some previously existing minerals which were replaced by quartz.

Although many factors are involved in the formation of vacuole-inclusions, it seems evident that a release of volatile constituents immediately previous to the crystallization of the quartz is of primary importance. Air bubbles in ice might furnish a possible analogy. In the case of quartz, however, the sources and the segregation of the volatile matter are not so obvious. Perhaps the most plausible assumptions are that the volatiles were contained in the quartz solutions or that the volatile matter was released as a by-product of replacement processes. In the latter assumption a further distinction might be made as to whether the volatile matter came directly from the material replaced or whether it was expelled from the quartz solution as an incident of replacement.

Vacuole-inclusions are affected by microbrecciation and are not present in most of the later quartz. They are usually removed by the recrystallization that commonly follows microbrecciation. Phantom veinlets of clear quartz traversing turbid areas appear to be one of the results of these processes. Vacuole-inclusions are also removed by the later quartz commonly found adjacent to a portion of the boundary of a replacing mineral. This feature is especially noticeable if the replacing mineral is a sulphide. In all probability they are filled in with later quartz.

Ferguson noted the fact that vacuole-inclusions may radiate from points along the boundary of an ore mineral.[10] This may be the result of the accommodation of the quartz to differential stress set up by the growing sulphides; or perhaps in some cases this radiating pattern of vacuole-inclusions may have been present before the sulphides formed, through the active replacement along lines of vacuole-inclusions. Hence, focal points of convergence of vacuoles would have been particularly susceptible to replacement. In some sections it is seen that later ore minerals follow-

[10] *Op. cit.*

ing a line of vacuole-inclusions have been arrested by a cross fracture or changed to another line or plane of inclusions having a different direction.

METALLIZATION.

Replacement processes play a dominant rôle in the chief metallization period. These include the replacement of earlier quartz or

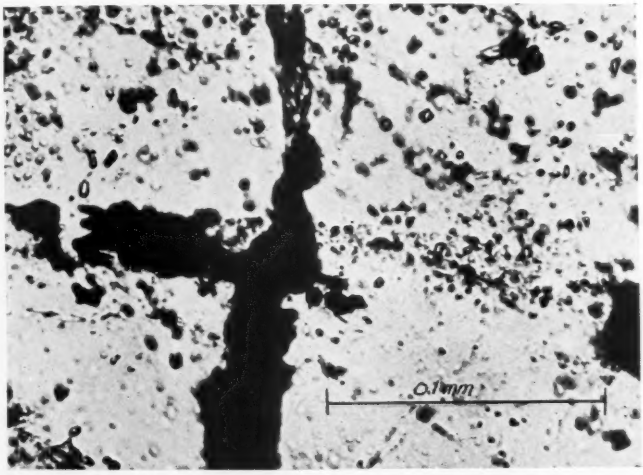

FIG. 5. A highly magnified section from the Red Jacket vein. Turbid quartz is filled with vacuole-inclusions and traversed by a veinlet of telluride and some native gold. The ore minerals appear in part to have replaced the quartz by a vacuole by vacuole advance.

earlier sulphides by later ore minerals. The character of the boundaries between the earlier quartz and replacing ore minerals vary considerably even within short distances. Under high magnification minute projections of sulphide or telluride are visible, commonly proceeding from a fracture along lines of vacuoles in the quartz. In some sections, replacement of the earlier quartz has apparently taken place vacuole by vacuole somewhat like the soaking up of a sponge (Fig. 5). As might be expected, the

features just described give rise to irregular boundaries and show many small irregular branching veinlets of sulphide into the quartz. Not all of the sulphide boundary, however, is irregular, for it is common to have a smoother outline of the ore mineral separated from the turbid quartz by a band of clear quartz, and in some cases there are connecting veinlets of clear quartz branching off in any direction from the border zones of clear quartz.

Since metalliferous solutions replace quartz it is obvious that silica is taken into solution as the ore mineral is precipitated. Hence silica is added to these solutions and under the complex and extremely variable physical-chemical conditions of vein formation some of this silica might be released at any stage in the process. This released silica could easily soak into the vacuole-inclusions of the earlier quartz so that as recrystallization took place these vacuole-inclusions would become filled and hence clear quartz would result. Many sections of the Cornucopia veins offer data supporting this interpretation. One section (Fig. 6) from the Union Companion vein shows chalcopyrite apparently replacing earlier quartz by injections through the vacuole-inclusions along one portion of its boundary, with the earlier quartz, and at an adjacent portion of the same boundary later quartz has been formed. High magnification shows that the boundaries of the chalcopyrite and the earlier quartz are clearly indicative of replacement and injection whereas the boundaries of the sulphide and the clear later quartz denote contemporaneity of formation with a slight suggestion of a partial resolution of the sulphide. In this section the clear later quartz although having the appearance of a later veinlet is in optical continuity with adjacent anhedra of earlier turbid quartz (Fig. 7). Some sections even show a veining of the sulphide by the later quartz.

These interpretations of solution and precipitation nearly coinciding in point of time and place may appear to be improbable if not impossible. Present day knowledge of the chemical nature of hydrothermal solutions is by no means complete. Lindgren, in his discussion of mesothermal deposits, states that evidences of colloidal deposition are found in many places in mesothermal

deposits, although far less commonly than in epithermal deposits. He is also of the opinion that gold in quartz veins was probably transported in the colloidal state.[11] Kidd and Haycock state that all evidence points to colloidal solutions in the case of the ores of

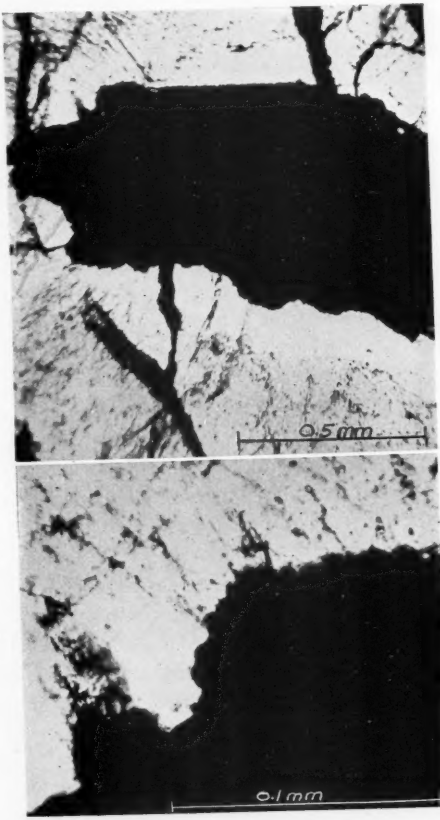

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FIG. 6. Photomicrograph of a section from the Union Companion vein showing chalcopyrite black replacing earlier quartz by advancing along lines of vacuole-inclusions. The lower right boundary is bordered with later clear quartz free from vacuole-inclusions.

FIG. 7. Part of Fig. 6 highly magnified showing the replacement.

[11] Lindgren, W.: Mineral Deposits. 4th Edit., Chap. XXVI, McGraw Hill, 1933.

Great Bear lake.[12] On the other hand, Gruner has recently pointed out that the abundance of electrolytes in hydrothermal solutions would probably prevent the formation of colloids or cause them to coagulate.[13]

Perhaps the apparent coincidence of solution and precipitation may be explained by the fact that physical chemical investigations with colloidal solutions have shown that minute changes in the pH value of the system, changes too small to influence ordinary indicators, are sufficient to cause precipitation.[14] These theoretical considerations all point to very critical physical-chemical conditions for vein forming solutions and appear to be substantiated by the petrographic data.

The ore minerals range from those indicative of lower mesothermal origin in the lower levels to those more characteristic of upper mesothermal deposits in the upper levels. Pyrite and pyrrhotite are conspicuous in the Union Companion vein some 1400 feet below the outcrop at a horizon some 3000 feet vertically below the highest outcrops of some of the other veins. Pyrite is persistent through to the upper levels; pyrrhotite is found only in the lower levels. Sphalerite, galena, chalcopyrite, tetrahedrite, tellurides and some native gold appear in the upper portions of the veins. The relative abundance of these minerals is by no means uniform; galena predominates in one of the veins, tellurides are conspicuous in some of the smaller veins. A rough statement of the paragenesis beginning with the earlier formed minerals is: pyrite and pyrrhotite, sphalerite, galena, chalcopyrite, tetrahedrite, tellurides, and native gold. This order varies slightly from the one given by Lindgren for mesothermal deposits in that chalcopyrite replaces galena and tetrahedrite replaces chalcopyrite.[15] Later pyrite is common, occurring contemporaneously with the

[12] Kidd, D. F., and Haycock, M. H.: Ores of Great Bear Lake. Bull. Geol. Soc. Amer., vol. 46, pp. 879–959, 1935.

[13] Gruner, J. W.: The solubilities of metallic sulphides in alkali sulphide solutions. Econ. Geol., vol. 28, pp. 773–777, 1933.

[14] Tarter, H. V., and Lorah, J. R.: The influence of hydrogen-ion concentration on the protective action of gelatin on Zsigmondy's standard gold sol. Jour. Phys. Chem., vol. 29, pp. 792–798, 1925.

[15] Lindgren, W.: *op. cit.*, Chap. 26.

chalcopyrite and galena. It is associated with the finer grained later quartz and is readily distinguished from the earlier pyrite. Earlier pyrite develops a tendency to idiomorphism with the earlier quartz and all stages of replacement of earlier pyrite by the later ore minerals are common. Fracturing of the pyrite is common and much of the later replacement has started along such fractures, some of which are healed by later quartz.

Pyrrhotite probably was formed at the same time as the earlier pyrite. Although lack of idiomorphism is apparent, the boundaries between this sulphide and contemporaneous quartz are relatively smooth. In some sections quartz has developed its crystal form against the pyrrhotite. This condition is shown in one section where part of a quartz crystal has approached idiomorphism with respect to pyrrhotite and where both the quartz and the sulphide replace a sericite-carbonate alteration aggregate. Portions of the boundaries indicate that the pyrrhotite has replaced some of the quartz. Other interesting features of this section are the presence of vacuole-inclusions in the quartz, probably formed as products of the sericite-carbonate replacement, and the development of larger individuals of muscovite, formed perhaps as a released mineral and in any case as a recrystallization product from sericite. Other sections show an intimate intergrowth of large flakes of muscovite with pyrrhotite, an indication of a somewhat higher temperature for the earlier stages of vein formation (Fig. 8).

Pyrite, the dominant earlier sulphide of the Cornucopia veins, carries only small values in gold and silver. The major amounts of these metals are associated with the later sulphides as well as with tellurides and native gold. Hence, the locus of deposition of the later minerals forms the ore shoots of the veins. The later sulphides replace earlier pyrite, replace one another as outlined in the paragenesis given above, and also replace the earlier turbid quartz. They occur in areas of microbrecciation, and are associated with later quartz and locally with some later carbonate. It seems probable that the slickensides, fractures and microbreccia-

tion caused by continuing movement during the period of vein formation, have played an important part in facilitating the access of the later metalliferous solutions. The previous distribution of earlier pyrite and the vacuole-inclusions of the earlier quartz have also influenced the precipitation of the later ore minerals.

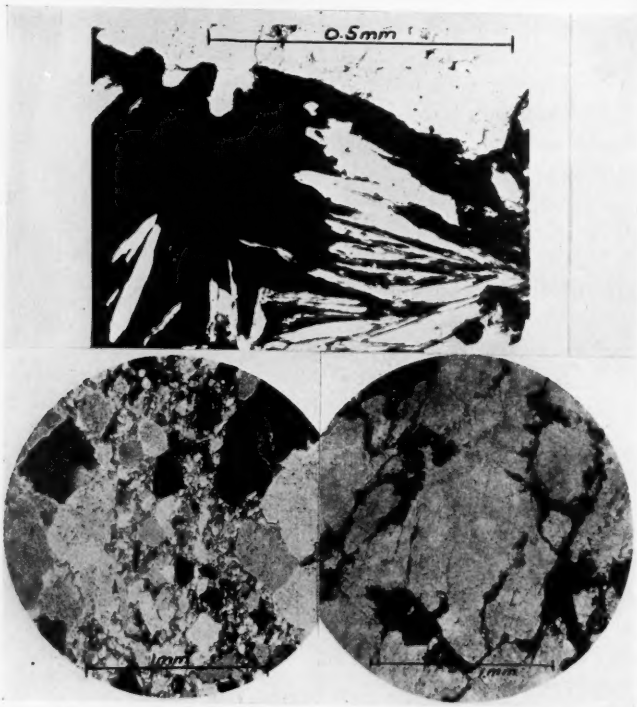

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FIG. 8. Association of sericite and pyrrhotite; section from the Union Companion vein.

FIG. 9. Photomicrograph of a section from the Last Chance vein; microbrecciation and recementation with later quartz is evident.

FIG. 10. Photomicrograph of a section from the Red Jacket vein showing tellurides in a zone of microbrecciation.

In 1925, Shannon described a telluride from the Last Chance vein as petzite occurring as a massive mineral intimately associated with calcite. He stated that it contained 1 per cent. chalcopyrite

and gave the following analysis:[16] SiO_2, 0.60; Au, 23.04; Ag, 42.00; Fe, 0.44; Cu, 0.32; S, 0.12; Te, 33.44. Studies of numerous polished sections indicate that the Cornucopia tellurides are not simple minerals but are intergrowths of petzite, hessite, sylvanite, and native gold. In polished section petzite has a smoother surface than hessite although it generally shows cleavage pits. It is isotropic in polarized light and hessite is slightly anisotropic. Microchemical tests show the presence of gold in the hessite. In some of the sections, petzite occurs in large areas surrounded by hessite with irregular although even boundaries. Other sections show rod-like intergrowths of petzite in hessite and others exhibit irregular intimate intergrowths of these minerals. Sylvanite generally appears with regular boundaries and is not as abundant as the other tellurides, although pockets of this mineral have been found in the Cornucopia veins.[17] Native gold may show a sharp contact with the tellurides or a gradational one.

The chief occurrences of tellurides in the Cornucopia district have been in the upper levels of the Last Chance vein and in the upper workings of the Red Jacket mine.[18] In the Last Chance mine, tellurides have been found on the 1600 level some 2200 feet, on the vein, below the outcrop. They have also been found in the veins intersected by the low level Coulter tunnel. They are confined to the later metallization and generally occur in veins not over 2 feet wide or in irregular quartz lenses traversing larger veins. They are associated with microbrecciation, and replace quartz and earlier sulphides (Fig. 10). The tellurides have interstitial relationship with the later quartz and are roughly contemporaneous with carbonate (calcite), chloritic material and native gold. Thin films of tellurides commonly surround earlier pyrite and may occur as minute veinlets in the sulphide. Many sections show a partial to a complete replacement of the pyrite by the telluride. With sphalerite as the host, the replacement has apparently taken place in small irregular blebs rather than along frac-

[16] Shannon, E. V.: Petzite from the Last Chance mine, Cornucopia district, Oregon. Washington Acad. Sci. Jour., vol. 15, no. 14, pp. 342–44.

[17] Lindgren, W.: *op. cit.*, 22d Annual Rept.

[18] Goodspeed, G. E.: Tellurides at Cornucopia, Oregon. Eng. and Min. Jour., vol. 136, no. 2, pp. 72, 73, 1935.

tures so that the result is similar to a dissemination. These contrasting modes of association may be due to the well developed cleavage and the brittle hardness of pyrite. Tellurides in small quantities are not easily detected, except by microchemical methods. In the Cornucopia veins the presence of even small amounts of free gold is generally indicative of tellurides, and it is possible that at least some of the gold values of the sulphides may be due to small amounts of tellurides disseminated along minute fractures or cleavage cracks.

The association of free gold and tellurides is such as to point to a common solution of gold, silver, and tellurium. Free gold occurs at the ends of many petzite veinlets and commonly bears a peripheral relation to petzite, especially where the telluride has replaced earlier pyrite. It also occurs in veinlets interstitial to later quartz and some sections show an intimate fibrous-like intergrowth of gold, carbonate, and chloritic material. Perhaps these later metalliferous solutions became too impoverished in tellurium to permit the formation of a telluride and hence gold was deposited in the free state. Another factor may have been the addition of iron and sulphur incident to the replacement of pyrite.

Under high magnification some sections show that native gold replaces the earlier vacuole-inclusion filled quartz in a manner similar to the other ore minerals; that is, by a vacuole to vacuole advance (Fig. 5). Gold also occurs in minute films around grains of later quartz and with calcite in minute veinlets. Dull finely divided mossy gold found in the surface outcrops of some of the veins may have been directly derived from the oxidation of petzite, as the occurrence is similar to that of the telluride, and as microchemical tests show the presence of tellurium. Furthermore, a yellowish stain associated with quartz containing this kind of gold contains tellurium no doubt in the form of the oxide tellurite. This gold is very different from the bright vein gold. The full variety has been termed mustard gold.[19]

[19] Maclaren, J. M.: Gold. Min. Jour., p. 28, London, 1908.

CONCLUSIONS.

Seritization and carbonatization of the wall rocks and of rock fragments in those portions of the veins that consist chiefly of earlier quartz suggest that emanations rich in carbon dioxide and perhaps in alkalies preceded the quartz forming period. It is clearly evident that earlier quartz replaced sericite-carbonate alteration material. That carbonatization continued throughout the process of vein formation is shown by the presence of calcite veinlets, by the occurrence of calcite as a matrix in some of the coarser types of microbrecciation, and by its common association with the later metallization. Some sections show a band of carbonate surrounding portions of later ore minerals. The origin of this carbonate may, in part, be similar to that of the bands of clear quartz *i.e.*, a by-product of replacement processes. Some of the coarser microbreccias of quartz and calcite are formed by replacement of quartz by calcite. The latest metallization, that of the tellurides and free gold, was accompanied in many cases by carbonate which was contemporaneous or a little later than the later quartz.

There are many structural field relations which might have a direct or indirect effect throughout the entire period of vein formation. Among these are the character of the initial fissures, the kind of rocks, traversed by these fissures, the movement along the plane of the vein allowing an easy access for vein solutions, and the decrease in temperature, which would be roughly proportional to the distance from the source of the vein forming solutions. Slickenside striations are prominent in the Last Chance vein and for the most part they rake to the south in the plane of this westward dipping vein. Thin sections from slickensided quartz show marked undulatory extinction, brecciation, and what appears to be multiple twinning. The general distribution of ore minerals indicates gradational temperature changes although local occurrences of small veins may introduce local modifications. The range of the tellurides is noteworthy.

In a summary of the petrographic character of the Cornucopia veins the following features should be mentioned. (1) Seritization and carbonatization preceding the main quartz-forming period. (2) The replacement of the altered wall rock by quartz as perhaps a dominant process of vein formation. (3) Concomitant metallization at this stage and continued carbonatization. (4) Microbrecciation, accompanied by the replacement of earlier sulphides and the replacement of earlier quartz by later ore minerals, which are associated with later quartz and carbonate.

These successive changes in mineralization offer an explanation of some of the local problems concerning abrupt variations in the tenor of the Cornucopia veins and may suggest an explanation for complicated mineral associations in other regions. In petrographic literature, quartz veins have been described under various headings and many interpretations of origin have been postulated. Hulin,[20] and more recently Berg [21] and Furnival [22] have emphasized the continual fracturing within veins during the period of formation and in this regard the Cornucopia veins appear to support their contentions. These studies suggest that in addition to the mechanical factor of brecciation, replacement processes play an important rôle in all stages of vein formation.

UNIVERSITY OF WASHINGTON,
SEATTLE, WASHINGTON,
March 28, 1936.

[20] Hulin, C. D.: Structural control of ore deposition. ECON. GEOL., vol. 24, pp. 15–50, 1929.

[21] Berg, George: Vein filling during the opening of fissures. ECON. GEOL. vol. 27, pp. 87–94, 1932.

[22] Furnival, G. F.: The large quartz veins of Great Bear Lake, Canada. ECON. GEOL., vol. 30, pp. 843–859, 1935.

NODULAR, ORBICULAR, AND BANDED CHROMITE IN NORTHERN CALIFORNIA.[1]

W. D. JOHNSTON, JR.

INTRODUCTION.

In 1930 Mr. A. F. Duggleby gave me a specimen of orbicular chromite from the Octopus claim, in Siskiyou County, Calif., showing two generations of chromite, one older than the associated olivine and one younger. In November, 1931, I examined briefly a number of deposits in northern California, in search for chromite showing similar and related textures. Some of the more unusual and genetically significant occurrences are described in this paper.

Most of the chromite localities here described are in Siskiyou County, northern California. Localities 1 and 2 are in the Seiad Quadrangle, where a belt of chromite-bearing dunite, striking northwest, extends from McGuffy Creek, near Scott Bar, into Oregon. Other deposits are in southern Siskiyou, Shasta, and Trinity Counties.

LOCALITIES.

1. Prospect on Seiad Creek, 5 miles above its junction with the Klamath River in Sec. 33, T. 47 N., R. 11 W., Siskiyou County, Calif. The location of the prospect is marked on the topographic map of the Seiad Quadrangle.

2. Prospects on McGuffy Creek, in Secs. 23 and 25, T. 45 N., R. 11 W., and Sec. 31, T. 45 N., R. 10 W. McGuffy Creek, a tributary to the Scott River, is in the west-central part of the Seiad Quadrangle, two miles south of Scott Bar. In 1917, a number of chrome prospects were opened on the ridge south of the creek and on the south side of the valley near the head of the creek, 2,000 to 3,500 feet above the Scott River. The principal chromite exposures are on the Octopus, Red Butte, Liberty, Neptune and Jumbo claims. Most of the chromite occurs as bands in dunite.

[1] Published by permission of the Director, U. S. Geological Survey, Washington, D. C.

Nodular chromite (Fig. 6) was found at two of the prospects and orbicular chromite (Figs. 1, 2) was collected on the Octopus claim. I am indebted to Mr. Herman Weeks, of Scott Bar, who guided me during the day spent on McGuffy Creek and who later sent me specimens of nodular ore from croppings on Tom Martin Peak which I did not visit.

3. Prospect in Trinity County on Crow Creek, 20.7 miles from Castella, on the Forest Service road to the Altoona mine. There is a small open cut approximately half a mile up a ravine from a loading platform on the road. Most of the chromite occurs as disseminated grains in serpentine, whose texture suggests derivation from saxonite, but a small amount of nodular chromite was observed.

4. The Coggins mine in Shasta County, Calif., near the Shasta-Siskiyou County line, is on the north side of Little Castle Creek, three miles southwest of Dunsmuir. Lenses of chromite occur in serpentinized peridotite. Most of the chromite of the Coggins mine is either massive or granular, but many specimens of nodular ore were collected from the dump.

A half-mile up the creek from the Coggins mine and on the south side of the canyon is the Castle Craig mine, which has produced about 12,000 tons of marketable chromite from a single large lens.[2] No nodular chromite was obtained at this property, however.

5. At Gibson siding north of La Moine, Shasta County, Calif., a loading platform holds a few tons of ore mined in 1917. According to Logan,[3] this ore came from a deposit on Shotgun Creek about a mile above the Sacramento River. Some of the ore contained spherical nodules 1 to 3 cm. in diameter imbedded in serpentine. The deposit was not visited.

ORBICULAR CHROMITE.

Figure 1 is a drawing of a polished slab of orbicular chromite from the Octopus claim on McGuffy Creek, Siskiyou County, Calif., the only locality at which orbicular structure was observed. The drawing was prepared by carefully inking the chromite areas on a photograph of the slab and then bleaching the photograph. Figure 2 shows parts of two other polished specimens. The orbicular ore is made up of many spheroidal units, each of which consists of a nucleus of chromite surrounded by a shell with

[2] Diller, J. S.: Chromite in the Klamath Mountains, California and Oregon. U. S. Geol. Surv. Bull. 725, p. 10, 1921.

[3] Logan, C. A.: Manganese and Chromite in California. California State Min. Bur. Bull. 76, p. 182, 1918.

drawn-out pointed ends composed, in the main, of partially serpentinized olivine. Each nucleus is composed of a number of chromite crystals, which, because of varying orientation, show slight differences in luster in polished sections. Each sheath of olivine is surrounded by a thin outer sheath of chromite and commonly contains several concentric layers of chromite. Larger masses of chromite occupy the interstices between abutting units. In a few units, the chromite nucleus is absent, and in a single small specimen (Fig. 3) the interstitial chromite is more abundant than the nuclear chromite.

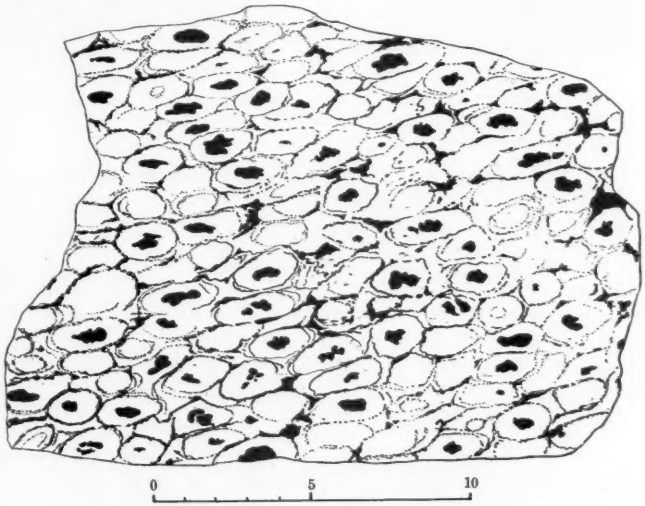

FIG. 1. Tracing from a polished slab of orbicular chromite, Octopus claim, Siskiyou County, Calif. The scale is in centimeters.

The drawn-out spheroids are fitted together in parallel orientation. The elongation of the orbicular ore is linear and not platy, for cross sections normal to the long axis of the units show only circular patterns.

Samples of nuclear and interstitial chromite were carefully chipped from the polished slabs shown in Fig. 2, ground to pass

200-mesh, separated from the lighter constituents in Clerici solution of 4.0 specific gravity, and analyzed for Cr_2O_3 in the chemical laboratory of the U. S. Geological Survey. Samples *a* and *c* are nuclear chromite and samples *b* and *d* are interstitial chromite.

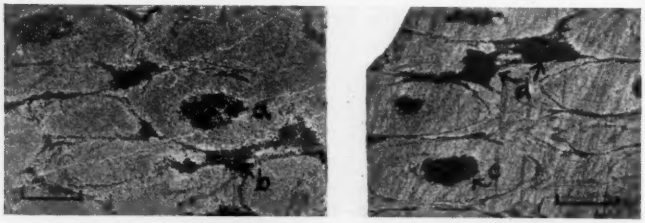

FIG. 2. Orbicular chromite showing nuclear and interstitial samples analyzed for Cr_2O_3., scale line = 1 cm.

ANALYSIS OF NUCLEAR AND INTERSTITIAL CHROMITE FROM THE OCTOPUS CLAIM SISKIYOU COUNTY, CALIFORNIA.
Charles Milton, Analyst.

	a	*b*	*c*	*d*
Cr_2O_3.....	46.42	51.56	52.93	52.48

Although the nuclear sample *a* contains 5 per cent. less Cr_2O_3 than the corresponding interstitial sample *b*, the close agreement of the pair *c* and *d* indicates that the two types have essentially the same Cr_2O_3 content. If they are to be distinguished chemically, a more complete analysis is necessary.

Despite the similarity in Cr_2O_3 content, the structure of the orbicular ore definitely suggests that the chromite nuclei acted as growth centers for the olivine, as did fragments of granite or diorite in many orbicular granites,[4] and that the interstitial chromite was introduced after the olivine shells had formed.

The orbicular structures have undergone deformation, as is witnessed by the linear arrangement of the constituent shells. It

[4] Sederholm, J. J.: On Orbicular Granites. Comm. géol. Finlande. Bull. 83, p. 65, 1928.

seems probable that deformation took place, presumably by flowage, before crystallization was complete, whereas the individual crystals of the olivine shells were only partially cemented, and the shells could be compacted and elongated without fracturing. The chromite-bearing dunite which forms the country rock of the orbicular chromite ore has a platy banding, of steep dip and northwesterly strike, which appears to be a flow structure. The structure is especially well exposed in the Red Butte claim (Fig. 7-*A*). If the linear elongation of the spheroids in the orbicular ore is due to flowage, the axes of the spheroids should lie parallel to the platy parting of the country rock; unfortunately, however, this relation cannot be observed, for all the orbicular ore observed was on the dump of the Octopus claim, none having been found in place.

FIG. 3. Olivine lentils surrounded by younger chromite. Octopus claim, McGuffy Creek, Siskiyou County, Calif.

FIG. 4. Nodular chromite from Briggs Creek, Josephine County, Oregon. The matrix is serpentine. Drawn from a specimen figured by Diller (U. S. Nat. Museum No. 91296); scale in centimeters.

NODULAR CHROMITE.

Nodular chromite is characterized by rounded nodules of chromite in a matrix of olivine, pyroxene or their alteration products. The terms "grape" or "bean" ore have been fittingly applied. Such textures seem to be of relatively common occurrence, for they have been reported from a number of localities. Diller[5] described two specimens, one from Josephine County, Oregon (Fig. 4), and the other from Eldorado County, Calif. (Fig. 6-*C*). Logan[6] published a photograph of "bean ore" from the Coggins chrome mine, Siskiyou County, Calif., and Burchard[7] figured a specimen of nodular chromite from Cuba. Denis[8] observed "grape ore" at two localities in Quebec and kindly furnished me with a photograph of one of his specimens, from which Fig. 5 was drawn.

In the Seiad Quadrangle, nodular chromite occurs in some of the McGuffy Creek deposits. Figure 6-*D* is a photograph of a polished slab of nodular ore from an exposure on Tom Martin Peak. The nodules are ovoid, averaging 1 cm. in length, and are composed of interlocking grains of chromite. They show a linear and not a platy orientation. By careful chipping individual nodules may be broken free from the matrix of serpentinized dunite. Figure 7-*E* is a photograph of a polished slab from the Neptune claim. A single large nodule, $1\frac{1}{2} \times 2$ cm., lies in olivine containing bands of disseminated chromite. A narrow shell of highly serpentinized dunite surrounds it.

At the Coggins mine, in Shasta County, nodular or "bean ore" is abundant (Fig. 6-*A*). The nodules vary in size from 0.5 cm. to 3 cm. in length and commonly show a platy elongation, parallel to the elongation of the larger lenticular mass in which they

[5] Diller, J. S.: *Op cit.*, pp. 11–13, pl. 2-A, 1921.

[6] Logan, C. A.: *Op. cit.*, p. 193, pl. 45.

[7] Burchard, E. F.: Chrome-ore deposits in Cuba. Amer. Inst. Min. and Met. Eng., Bull. 153, fig. 5, 1919; Trans., vol. 63, pp. 150–174, 1920.

[8] Denis, Bertrand T.: The chromite deposits of the eastern townships of the Province of Quebec. Quebec Bur. Mines, Ann. Rept. for 1931, pt. D, pp. 30–31, 1932.

occur.[9] On weathered surfaces the interstitial serpentine is first removed and the residual chromite nodules take on the appearance of "bean ore."[10]

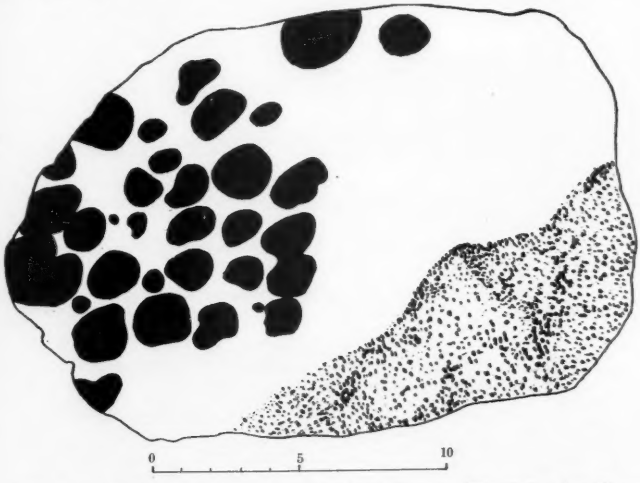

FIG. 5. "Grape ore" from the Standard Chrome Pit, Coleraine Township, Quebec. Chromite nodules and disseminated grains are shown in black and the matrix is serpentinized dunite. Traced from a photograph kindly furnished by Mr. B. T. Denis; scale in centimeters.

The spherical chromite nodules in the ore from Gibson siding are larger, averaging 2 cm. in diameter, and show no orientation (Fig. 6-*B*).

The nodules from the prospect on Crow Creek, in Trinity County, are faintly ovoid and average 0.5 to 1 cm. in diameter. A single specimen was obtained in which irregularly shaped nodules of serpentine less than 0.5 cm. in diameter were contained in a matrix of chromite.

A specimen from the Placer Chrome mine, Eldorado County (Fig. 6-*C*), described by Diller,[11] has a matrix of serpentine and tremolite, and veinlets of serpentine cut the chromite nodules.

[9] Diller, J. S.: *Op. cit.*, fig. 3, p. 10.
[10] Logan, C. A.: *Op. cit.*, pl. 45.

Regarding the chromite nodules in the Quebec ores, Denis says:[12] "The natural inference of the origin of these 'grapes' would appear to be that they represent centers to which the chromite was attracted from the surrounding rock during its solidification."

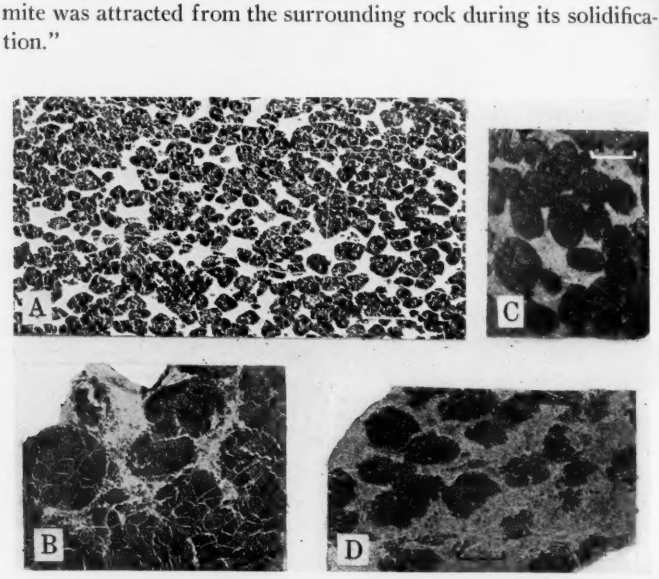

FIG. 6. Polished sections of nodular chromite. *A*, Coggins mine, Shasta County, serpentine matrix. *B*, Gibson siding, Shasta County, serpentine matrix. *C*, Placer chrome mine, Eldorado County, tremolite matrix. *D*, Tom Martin Peak, Siskiyou County, serpentinized dunite matrix. Scale line = 1 cm.

BANDED CHROMITE.

Diller[13] called attention to the banded ores of the Siskiyou County deposits and published a plate showing several polished

[11] Diller, J. S.: *Op. cit.*, p. 12.
[12] Denis, B. T.: *Op. cit.*, p. 31.
[13] Diller, J. S.: *Op. cit.*, pp. 13–14, pl. 3.

slabs of banded ore. Rogers[14] and Maxon[15] have studied banded deposits both in Siskiyou and in Del Norte Counties.

The deposit on Seiad Creek is characterized by the sharply defined bands of chromite in serpentinized dunite. The bands are of variable width and continuity. Some bands a few inches in width can be traced along the strike for 20 feet or more before they grade into the country rock or are faulted by minor slips at right angles to the banding (Fig. 7-*B*); others are more irregular. Some of the rock is finely banded with alternate layers of olivine and chromite and resembles a banded sandstone (Fig. 7-*D*). The banding near-by is contorted and strongly suggests flow structure. There are occasional bands several inches to a foot in width of almost pure chromite. An analysis of ore from one such band was made by Charles Milton, of the U. S. Geological Survey. The sample was ground to pass 100-mesh and separated from the lighter components in Clerici solution (sp. g. 4.0).

Most of the chromite in the McGuffy Creek deposits is banded. The bands are irregular in extent and changeable in dip, but the general strike is to the northwest. Many bands strongly suggest

ANALYSIS OF CHROMITE FROM THE SEIAD CREEK DEPOSIT, SISKIYOU COUNTY, CALIFORNIA.

Charles Milton, Analyst.

	A	*B*
Cr_2O_3	57.92	59.19
Al_2O_3	5.84	5.97
Fe_2O_3	6.40	6.54
FeO	14.83	15.16
MnO	.25	.25
NiO	.06	.06
MgO	13.12	12.73
CaO	.26	
SiO_2	1.29	
Total	99.97	

A. As analyzed. *B*. After deducting 2.2 per cent for (Ca, Mg) SiO_3, assumed to be present as an impurity.

[14] Rogers, A. F.: Chromite in the Dunite of Northwest Siskiyou County, California (Abstract). Geol. Soc. Am. Bull., vol. 43, p. 232, 1932.

[15] Maxon, J. H.: Contact Conditions of Some Chromite Deposits in Serpentine in the Klamath Mountains (Abstract). Geol. Soc. Am. Bull., vol. 44, p. 166, 1933.

flow structure (Fig. 7-*A*). In places the banded rock is folded and faulted, and the fault planes are occupied by pyroxenite dikes.

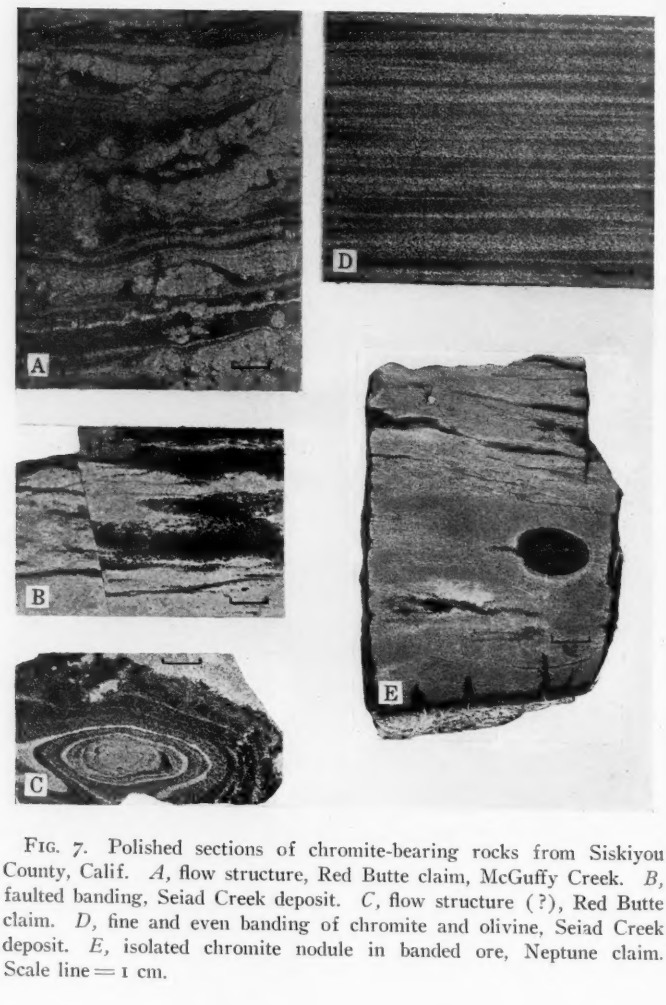

FIG. 7. Polished sections of chromite-bearing rocks from Siskiyou County, Calif. *A*, flow structure, Red Butte claim, McGuffy Creek. *B*, faulted banding, Seiad Creek deposit. *C*, flow structure (?), Red Butte claim. *D*, fine and even banding of chromite and olivine, Seiad Creek deposit. *E*, isolated chromite nodule in banded ore, Neptune claim. Scale line = 1 cm.

Of the Seiad Creek deposits Rogers[16] says: "A preliminary study of these ores indicates that the chromite was formed at a late magmatic stage as in other types of magmatic ores."

GENETIC SIGNIFICANCE OF THE STRUCTURES.

The suggestion of flow structure in many of the banded ores has already been mentioned. Kato,[17] who studied similar banded ores in Japan, says: ". . . it is highly probable that the banded ore was formed by a flowing motion of the crystallized dunite magma, in which settling of the chromite crystals was going on." Maxon[18] regarded the banded ores of northern California as primary flow structures. Such an interpretation appears to be in agreement with all the observational data at hand, for the flowage that produced banding would likewise produce the linear orientation observed in both the nodular and orbicular ore.

The nodules and the nuclei of the orbicular ore are older than the olivine or pyroxene that incloses them and hence belong to the early magmatic stage of Fisher[19] and Sampson.[20] The interstitial chromite of the orbicular ore is younger than the olivine and may belong to the late magmatic stage.

Final interpretation of the structures must await detailed geological mapping of the areal geology, for their relation to contacts is of prime genetic importance.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
Jan. 18, 1936.

16 Rogers, Austin F.: *Op. cit.*, p. 232.

17 Kato, Takeo: Notes on the Banded Chromite Ore from the Akaishi Mine in the Province of Iyo, Japan. Jour. Geol. Soc. Tokyo, vol. 28, no. 331, pp. 16–17, 1921.

18 Maxon, J. H.: *Op. cit.*, p. 166.

19 Fisher, L. W.: Origin of Chromite Deposits. ECON. GEOL., vol. 24, p. 719, 1929.

20 Sampson, Edward: Varieties of Chromite Deposits. ECON. GEOL., vol. 25, p. 834, 1931.

system that has long ceased to exist cannot be fully determined, but nevertheless the lack of definition was largely Fenner's own, since an essential part of the picture was omitted from his discussion, when these carbonates were not mentioned.

Fenner gives reasons for doubting the significance of the absence of titanium minerals, despite the volatility of titanium haloids. This was the least significant of all the relations cited and could well have been omitted from my paper. On the other hand he only raises the general question as to whether a correspondence between volatilities and proportions of materials deposited is to be expected; and does not discuss the specific group composed of calcium, magnesium, and iron carbonate, or how calcium with an extraordinary low vapor pressure could have been segregated as a vapor phase. It is true that materials of low vapor pressure may be carried over together with those with a higher pressure (partial pressure effect), but there is every reason to believe that concentrations would be small for calcium and magnesium, and the relationship to volatilities would not be completely reversed. In the absence of definite evidence against its validity, the absence of a relationship between proportions of materials present and their volatilities, is at least corroborative evidence against vapor phase transportation.

Fenner also fails to discuss the even more significant fact that calcium carbonate, magnesium carbonate, and iron carbonate were commonly formed in the proportions and in the exact sequence that would be expected if they were deposited from liquid solutions.

Another problem that has not been met by the theory of vapor transportation is the removal of large quantities of quartz by the medium that introduced the carbonates in ore bodies of the Ducktown type. Small areas of residual quartz completely enclosed in calcite imply direct replacement of quartz—that is, no lag between solution of quartz and deposition of calcite. These residual grains could not have remained suspended in space while awaiting a change in environment that permitted the deposition of carbonates. Moreover, a replacement by some intermediate

material that was later completely removed by calcite seems to be very definitely precluded.

N. L. Bowen in the Lindgren volume [2] has discussed the "character of the vapor phase from boiling pegmatitic liquid" and says "Certain ingredients such as H_2O and F, and the like, will contribute to the gas phase in large amount and certain others such as CaO will be practically absent . . . though certain substances not usually to be regarded as volatile may enter the gas phase in notable amounts; as for example, iron and titanium in virtue of their capacity to form volatile halogen compounds."

. . . The vapor formed by the boiling of the alkaline residual liquors of magmas will be acid, in that it contains an excess of HCl, HF, H_2S, CO_2, H_3BO_3, and H_2SO_4, and other more or less volatile acids." Thus a vapor phase distilled over from a crystallizing magma, or liquids formed by the condensation or partial condensation of a vapor phase would be enriched in acid radicals. Bowen then proceeds to discuss the effects of this relation in a most enlightening way and his entire paper should be read by any one interested.

It seems obvious that silica could not have been dissolved and removed, and carbonates deposited by vapors that had, by the very mode of their formation, been enriched in acid forming elements; or by acid liquids formed by their condensation. Silicon fluorides are relatively volatile but calcium compounds have extremely low vapor pressures. Therefore, such vapors would be much more likely to introduce silica than to remove it, and acid rich vapors or acid liquids formed by condensation of these vapors would remove calcium and magnesium rather than deposit it.

The existence of acid bearing vapors or of acid rich liquids formed by their condensation seems to be definitely precluded at the point of deposition of carbonates, but this does not lessen the importance of the relations pointed out by Bowen. This is the only mechanism postulated that would give the acid liquids that many geologists believe are needed to explain certain types of

[2] Bowen N. L.: Broader story of magmatic differentiation briefly told. Ore Deposits of the Western States, Lindgren volume, pp. 106–128, 1933.

mineral deposits. It is probable that such acid solutions played an indirect part in the segregation of these materials. Vapors carrying acid forming radicals tend to condense or partly condense as they migrate to zones of lower temperatures. At first they would be actively acid and would tend to dissolve bases from the rocks with which they came in contact, and normally the most soluble bases would be present in greatest amount; although such factors as mass action, relative concentration in the parent rock, and relative alterability of the minerals effected would play their part. Deposition would be produced by cooling, neutralization, the escape of acid elements by renewed boiling, etc. Materials would be deposited in the inverse order of their solubilities, and the most soluble ones would be found farthest from their source. This picture seems to fit the relationships presented by the carbonates of the deposits of the Ducktown type with close fidelity.

The lack of a common ground for agreement between Doctor Fenner and me seems to be in large part due to the fact that much of the time we were not talking about the same thing. I was trying to account for a specific group of relations in a particular type of ore body, while much of his review was devoted to a discussion of the importance of vapor or gas phases in general. Thus, were we considering identical relationships we would probably not be as far apart as might appear. The applicability of gas or vapor phases to mineral deposition can be adequately discussed only when a definite picture is presented of all the processes involved in the segregation transportation and deposition of some specific group of minerals (these carbonates in this instance). Until this is done the theory of vapor, or gas phase mineralization remains little more than a suggestion that vapors play a more important part in mineral deposition than has sometimes been recognized. This I am fully willing to grant as a general proposition, but not for the carbonates occurring in the deposits of the Ducktown type.

CLARENCE S. ROSS.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
April, 2, 1936.

REVIEWS

Structural Geology, with special reference to economic deposits. By Bohuslav Stočes and Charles Henry White. Pp. xiv + 460, figs. 665. D. Van Nostrand Co., New York, 1935. Price $9.00.

In the introduction to this book the junior author states that it is an elaboration of a work of Dr. Stočes that has been published in Czech and German. The book has been rewritten and greatly expanded and the illustrations have been increased nearly twofold.

It is essentially an introductory treatise; the experienced field geologist will find little new material nor a thorough systematic discussion of older principles and criteria and the book can hardly take a place as a reference work. However, a considerable range of structural phenomena that may bear upon economic geology are considered and a beginning student is given enough examples to enable him to see the relation of the structure of many different deposits to their exploitation. That the applications of structural geology to ore finding (as distinct from mining) receive little attention is notable, but the omission is perhaps more the fault of the profession than of the authors. The field wherein geologists have made the greatest contribution in the search for economic deposits—petroleum geology—is treated rather perfunctorily and very little beyond the simple anticlinal theory is mentioned.

The organization of the book seems rather unsystematic: in the chapter on "Primary Structures of Sediments," a section on roof and floor of beds leads into discussions of folds and faults, of the effect of joints on roof support, and of the economic exploitation of certain coal mines; the topographic expression of rock hardness is also discussed here. The ecology of modern corals, a subject of intrinsic interest, hardly seems worth two pages in a book with the title of this one.

The authors are very dogmatic; alternative views are rarely presented. Thus cross-folds are "due to a second phase of folding acting at right angles to the direction of the principal folding" (p. 157) with no discussion of their possible localization by rock inhomogeneities in a single tectonic phase. Fragments in a fault breccia have "spherical sides and sharp edges," although probably few geologists would regard these features as diagnostic of fault breccias. A straight boundary of a basin (of sediments) indicates a fault (p. 217)—a statement that demands

some discussion of the scale of the phenomenon, the attitude of the sediments and other factors. On p. 224 it is said that "faults often serve as channels for underground water along which it comes to the surface in springs. A line of springs would therefore indicate the line of outcrop of a fault." No mention is made of topographic factors nor that stratigraphic controls may also produce lines of springs.

Spheroidal weathering, platy, rhomboidal and polyhedral structures of porphyries are all attributed to cooling, without discussion of other possible causes. Nickel sulphides due to magmatic differentiation occupy breccia cavities that are said to be formed by shrinkage of the norite on cooling. Contact deposits (p. 106) and dikes and mineral veins (pp. 178–179) are similarly localized. Although exceptions to some of these broad statements are later mentioned they are not placed in contrast with them.

Slickensides are said to show the direction of fault motion but no adequate warning is given of their unreliability. Similarly, there is, in the reviewer's opinion, undue emphasis on curvature of faults as showing their directions of possible motion. That fault drag may sometimes be deceptive is not mentioned until many pages after it has been described and endorsed in such terms as to make the unwary believe it an infallible clue to direction of displacement.

Many statements are far too sweeping for the facts, thus on p. 212 it is said that in folded regions there are *generally* two sets of faults, one longitudinal, the other transverse.

There appears to be too great an emphasis on dynamics and theory and not enough on kinetics, throughout, in spite of the fact that practical applications are clearly dependent on displacements of rocks and not on the forces involved in their displacement. Thus, despite a casual remark (that many would regard as a model of understatement) on p. 211, that the relation between fault trends and pressure is "not well understood," it is said, (p. 268) without further discussion, that "under regional stress the minerals are arranged in roughly parallel bands perpendicular to the active stress, forming a special class of rocks, the crystalline schists," and (p. 272) "the study of joints is important as they indicate the direction of orogenic pressure," without any hint as to how the reader is going to derive this information. Extremely hypothetical structural sequences to explain such features as transverse faults, horsts and rift valleys are given, without any warning as to the artificiality of the concepts and no discussion of alternative hypotheses (pp. 344–349). Thus transverse faults are said to form only where the older longitudinal dislocations are steeply inclined. That they have also been found in flat thrust sheets is not mentioned.

Butler's theory about the marginal relation of ore deposits to plateau and other positive areas is stated as an established generalization, though there are many dissenters.

Several terms are used in senses different from those common in America—for example "geological window" for inlier, "klippe" as a general synonym for "outlier," "strain" for tension (p. 142). The temperature gradients on the Salt Creek anticline, Wyoming, are said to be controlled by a salt deposit. Two contradictory definitions for "compound veins" are given on successive pages (pp. 291–292).

Despite this catalog (which could readily be extended) of what the reviewer regards as errors, the book has many good points. Of these the most outstanding are no doubt the profuse illustrations. Nearly all deal with European subjects and are relatively new to American readers. Those that show the relation of the attitude of beds to topography and to the width and trend of their outcrops, and the many that illustrate fault offsets are unusually clear. It seems unfortunate that many of doubtful value are included and there is a failure to stress some of the structurally significant features that are shown. For example, three distant views of ripple-marked sands are shown and one of a hand specimen of sandstone, but except for a phrase in the subtitle of one of these, there is no discussion of the diagnostic features that permit recognition of top and bottom of a bed. Cross-bedding is mentioned, but its value in structural work is not—graded bedding is not mentioned among the primary structural features, although hieroglyphics are; seven line drawings and a photograph are used to show that stream gravels commonly accumulate on the inner sides of meanders.

A brief section on geophysical methods is included. Stach's excellent devices for drawing up block diagrams are emphasized. The effect of various structural situations on the exploitation of mineral deposits is continually and effectively stressed. For these reasons the book is probably of value as collateral material for an introductory course in either structural or economic geology. It would be unfortunate to use it as a text. The literature references are almost wholly to general papers and seem little adapted, as a rule, to supplement the book in the field outlined in its subtitle.

The high price of the book will limit its distribution. It seems unfortunate that the many excellent illustrations, to whose inclusion the price is probably due, will therefore reach few beginning students who would profit most from them.

JAMES GILLULY.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
March 20, 1936.

Lehrbuch der Mineralogie, KLOCKMANN. 11th Ed. Revised and edited by PAUL RAMDOHR. Pp. xii + 625, Figs. 613. F. Enke, Stuttgart. Price (paper), 34 Rm.

Since the appearance of the 10th edition of Klockmann's Lehrbuch der Mineralogie the progress that has been made in the science of mineralogy has been so great, especially in its morphological and structural phases, that it has been found necessary in the revision for the 11th edition to rewrite completely the discussion of crystal morphology, to add a section on the investigation of crystal structure through the use of Röntgen-rays, one upon the relation existing between the structures, and another upon the physical and chemical properties of crystallized minerals, and to revise thoroughly the chapter on the origin and alteration of minerals. In the description of the individual minerals, many hundred errors are said to have been corrected and many observations have been recorded that had not hitherto appeared in text books.

The discussions of crystal forms (crystallography), of the structure of crystals and of their physical and optical properties, are exceptionally noteworthy. The use of Röntgen-rays in the investigation of mineral structure is outlined in sufficient fullness to be easily understood by the reader who is not a specialist in the subject. The treatment of the optical properties of crystals is also exceptionally well done, and the methods of determining them are briefly, but clearly described. Probably the most welcome chapter in the book is that which deals with the physical chemistry of crystals, and the explanation of diagrams illustrating the behavior of chemical systems under various conditions. Another interesting chapter is that which discusses the formation of minerals. This, though short, is a good introduction to the principles underlying petrology and ore deposition.

In short, the new edition must be regarded as probably the most modern textbook on minerals and their properties now in print.

W. S. BAYLEY.

Rochas Gondwanicas e Geologia do Petroleo do Brasil Meridional. By V. OPPENHEIM. Pp. viii + 129. Boletin N. 5, Nat. Dept. Miner. Prod., Republica dos Estados Unidos do Brasil, Rio de Janeiro, 1934.

During the long search for coal and oil in E. Brazil over 70 boreholes have been drilled, mainly by the Government, the deepest being 817 meters. This useful and profusely illustrated memoir, published by the new National Department of Mineral Production, summarizes not only the results of such boring, but all existing geological information concerning the immense Paraná Basin, and hence is up to date. The separately issued color-printed map on the scale of 1: 2,750,000 has 5 divisions for the Gondwana strata, and extends and corrects that of 1927 by the reviewer.

It brings out well the great transgression of the Triassic not only at opposite ends of the basin, but within it over the northern part of Rio Grande do Sul.

The rocks composing the Santa Catarina "System"—to use the new Brazilian spelling—are divided as follows:

		Meters
Rhætic	Serra Geral Eruptives	0–440
	Botucatu	50–120
Triassic	Rio do Rasto	70–150
	Estrada Nova (Upper)	50–200
	(Discordance)	
Permian	Estrada Nova (Lower)	50– 70
	Iratí ("Iratý")	40– 70
	Rio Bonito and Palermo	100–250
	Itararé (Glacial)	0–700

As elsewhere in Gondwanaland, the basal division rests unconformably upon older rocks and consists largely of tillites; the Rio Bonito contains the coals of Brazil (with a Glossopteris flora); the key zone of the Iratí consists of carbonaceous pyritic shales and calcareous layers: the Estrada Nova is argillaceous, varicolored in its upper part, which contains a molluskan fauna with *Myophoria;* the Rio do Rasto "red beds" carry vertebrates having alliances with those of the African Karroo: the Botucatú is largely an eolian sandstone accumulated under an arid climate. The succession ends with widespread plateau basalts emitted from fissures now occupied by sills or dikes of diabase, often dislocating and tilting the strata.

The author reviews all the petroliferous occurrences of the Southern Hemisphere and finds that nowhere have more than traces of oil been found in pre-Cretaceous Gondwana beds. The petroleum of Salta, Argentina, is viewed as having come from the underlying Devonian.

While suitable reservoir rocks occur within the Santa Catarina system, the sporadic petroliferous indications consist of bituminous matter along joints or in calcareous layers in the sediments or in vesicles in intrusive diabase, some of it being polymerized and approaching albertite. The gases are largely methane, and rarely under pressure. The hydrocarbons are regarded as secondary and derived through distillation by diabase dikes or water-transport from the bituminous Iratí shales.

In opposition to C. W. Washburne,[1] Oppenheim thinks it unlikely that petroleum will be found in commercial quantities in the Paraná Basin. The close parallel with South Africa should be emphasized; similar indications there can often be traced to the equivalent carbonaceous Dwyka shales ("White Band") or intrusions cutting the latter,—a resemblance

[1] Petroleum Geology of the State of São Paulo, Brasil. Bol. 22, Comm. Geogr. e Geol. do Estado de São Paulo, 1930.

extending even to the presence of saline (probably connate) water in both formations.

Supporting the author in his opinions, the reviewer thinks that the apparent lack of petroliferous substances in the Permo-Liassic Gondwana rocks of the world must be ascribed primarily to their peculiar mode of deposition—for the most part in shallow interior basins undergoing gentle warping in which the sediments were intermittently exposed and desiccated under a climate that was frequently semi-arid.

The memoir is an instructive one and deserving of wide attention.

ALEX L. DU TOIT.

Available Raw Materials for a Pacific Coast Iron Industry. By E. T. HODGE. 4 Vols. (mimeograph), pp. 103; 14 appendices of 761 pp.; pl. 29. War Department North Pacific Division, Portland, Oregon, 1935.

This extended report and compilation brings together all known information regarding raw materials available on the Pacific Coast for electric iron smelting in the Lower Columbia River Valley. The materials considered are iron ore, iron scrap, coke, carbonate rocks, silica, fire clays, chrome, and manganese. Costs, markets, and transportation are treated. The survey covers not only the Pacific coast of the United States, but the western United States, Alaska, Yukon, British Columbia, Mexico, Central America, South America, Cuba, Philippines, Japan, China, and other trans-Pacific and South Pacific countries. Geology is scanty but a wealth of valuable statistical data of resources is presented.

BOOKS RECEIVED.

L. B. RILEY.

Gold Deposits of the Elbow-Morton Area, Manitoba. C. H. STOCKWELL. Pp. 74, figs. 11, map. Can. Geol. Surv. Mem. 186. Ottawa, 1935. 25 cts. A prospecting area 38 mi. east of Flinflon. Pre-Cambrian rocks near the southern edge of the Canadian Shield contain shear zones with gold-bearing quartz. There is also some cherty quartz and some sulphide replacement bodies that carry gold.

Waswanipi Map Area, Northern Quebec. G. W. H. NORMAN. Pp. 8, map. Can. Geol. Surv. Prelim. Rept. 36–3. Ottawa, 1936. Shear zones in pre-Cambrian rocks contain quartz veins and lenses. The quartz carries gold and sulphides, and possibly tellurides; there are also lenses consisting principally of sulphides. This paper is the first received of a new series; it is mimeographed, on 8½ x 13 paper, with a white-print map. These reports issued soon after the field season should be of great value in an area of active prospecting.

Bibliography of North American Geology, 1933–1934. E. M. THOM. Pp. 389. U. S. Geol. Surv. Bull. 869. Washington, 1935. 40 cts. This recent addition to the well-known and valuable series contains 3836 entries from 256 publications.

Mining Royalties and Rents in the British Empire. Imperial Institute, Mineral Resources Dept. London, 1936. 3s. 6d. Pp. 183. An up-to-date and authoritative work, covering vested ownership, royalties, export duties and rents; coal, petroleum and natural gas, bituminous and oil shales, ores of iron and ferro-alloy metals, base metals, precious metals, precious stones and miscellaneous minerals are included.

Corundum in the Union of South Africa. W. KUPFERBURGER. Pp. 81. So. African Geol. Surv. Bull. 6. Pretoria, 1935. 6d. An account of the corundum deposits and their mining.

Geology of the Klerksdorp-Ventersdorp Area. L. T. NEL. Pp. 159, pls. 12, figs. 5. So. African Geol. Surv. Pretoria, 1935. 10s. 6d., including map (2 sheets). "This forms the explanation to the two geologic maps of the area." The area is 30 mi. southwest of the West Rand. Some gold has been found in rocks of the Witwatersrand System in this area, but the amounts realized are not comparable to the type locality, and the distribution of the gold shows great irregularity.

Chemical Analyses of the Rocks, Ores and Minerals of So. Rhodesia. E. GOLDING, analyst. Compilation and descriptions by A. E. PHAUP. Pp. 105. So. Rhodesia Geol. Surv. Bull. 29. Salisbury, 1936. 6s. 2d. Many of the rocks analyzed are from areas of interesting petrology.

Mineral Commerce and International Relations. EDWARD SAMPSON. Jour. Frank. Inst., Vol. 221, Jan., 1936. Following a survey of mineral commerce by materials and countries, a new method of rating is suggested consisting of production × importance, giving a figure of rating for each country thus affording ready comparison. These are summarized as a per cent. of the total world score for each country. It is ingenious, interesting, and valuable.

Canadian Mines Handbook, 1936. Pp. 367. Northern Miner Press. Toronto. Mar. 1936. Price $1.00. Covers all producing and inactive mining companies (3774) in Canada; lists officials, location, development, reserves, and financial matters.

Chemical Formulary. H. BENNETT, Editor. 32d Vol. Pp. 566. Van Nostrand Co., New York, 1936. Price $6.00. Practical formulas for making thousands of products in many fields of industry, which with the two preceding volumes covers all fields, with more than 15,000 formulas. Includes tables, common names of chemical products, where to buy chemicals, and 140 pages of index; compact, valuable.

SCIENTIFIC NOTES AND NEWS

H. Ries, professor of geology at Cornell University, lectured at Toronto University on April 17 on the Recent Developments in the Geology and Uses of the Non-Metallics.

The American Foundrymen's Association has awarded H. Ries of Cornell University the Seaman gold medal in recognition of his outstanding services to the foundry industry in the field of foundry sand research and control.

H. C. Horwood has resigned as assistant geologist of the Geological Survey of Canada, and is now geologist with the Ontario Department of Mines at Toronto.

R. F. Playter, geologist for the Lake View & Star, Ltd., left Fiji in December and has been visiting some of the mining districts of the United States.

T. W. Gevers is the new president of the Geological Society of S. Africa.

A. W. Rogers has been awarded the Draper Memorial Medal by the Geological Society of S. Africa.

Berlen C. Moneymaker, associate geologist for the TVA at Murphy, N. C., has recently spent six weeks in Puerto Rico on engineering geological work in connection with some of the power and irrigation dams being built.

S. H. Williston, economic geologist, of Aberdeen, Wash., after an examination made jointly with Milnor Roberts, of Seattle, has taken an option on the Horse Heaven mercury mine near Ashwood in north-central Oregon.

Guy C. Riddell, consulting mining engineer, expects to return to New York City in June or July, from Sinaloa, Mexico, where he has been engaged in professional work.

George H. Garrey, consulting mining engineer, of Denver, has been examining the properties of the Goldfields of America, Inc., near Manhattan, Nevada.

Kenneth Leith, mining geologist, is vice-president of the Burgess Titanium Co., at Amherst, Va.

Harold A. Titcomb, of Farmington, Me., is spending a few weeks in Florida.

J. H. Batcheller, head of the geology department at the Oregon State College, has been appointed on the consulting staff of the mines division of the Oregon Board of Vocational Education and will have an active interest in the Grants Pass Mining School. This school is being financed by WPA funds and is reported to have an enrollment of over 1100.